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AMS 100th Anniversary Monograph

Chapter 14: 100 YEARS OF PROGRESS IN HYDROLOGY

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Table of Contents

Abstract

The focus of this chapter is progress in hydrology for the last 100 years. During this period, we have seen a marked transition from practical engineering hydrology to fundamental developments in hydrologic science, including contributions to Earth system science. The first three sections in this chapter review advances in theory, observations, and hydrologic prediction. Building on this foundation, the growth of global hydrology, land-atmosphere interactions and coupling, ecohydrology, and water management are discussed, as well as a brief summary of emerging challenges and future directions. Although the review attempts to be comprehensive, the chapter offers greater coverage on surface hydrology and hydrometeorology for readers of this American Meteorological Society (AMS) Monograph.

1 Introduction: From Engineering to Hydrologic Science

The development of ancient civilizations along the Nile, Tigris-Euphrates, Indus, and Huang-Ho rivers is not an accident—proximity to water for drinking, sanitation, agriculture, and navigation enriched their livelihoods. Soon after these civilizations were established, they began to measure and manage water, including constructing flood control dams, collecting stream gauge information, and building irrigation canals (Noaman and El Quosy, 2017; Harrower, 2008; Chandra, 1990). There is evidence to support that these ancient civilizations understood the concept of the hydrologic cycle, including precipitation as the source of groundwater recharge through infiltration, and the role of solar radiation in evapotranspiration (Chow, 1964; Chandra, 1990). As summarized by Baker and Horton (1936), there were competing theories of the origin of springs and rivers by ancient philosophers from Aristotle, Vitruvius, and Ovid to Seneca, who described “Forms of Water” in his “Questions Naturalis”.

Many of these ideas remained in place until the Renaissance, when Leonardo da Vinci (ca. 1500) classified hydrologic processes using hypothesis-driven science, including the hydrologic cycle (Pfister et al. 2009). Almost 200 years later during the Scientific Revolution in the 16th and 17th centuries, the French writer Pierre Perrault was the first to take a quantitative approach to understanding the nature of the hydrologic cycle (Deming, 2014). In England, astronomer Edmond Halley also studied the hydrologic cycle. However, French Academy member Edme Mariotte was the first to quantitatively demonstrate a fundamental concept of hydrogeology, which is that precipitation and infiltration ultimately comprise streamflow (Deming, 2017). Mariotte also made fundamental contributions to hydrostatics and applied this knowledge to engineer the water supply at Versailles. Clearly from ancient times through the Scientific Revolution, advances in hydrologic science were often made by polymaths observing and testing their knowledge to support water management.

To meet the needs of flood design, land and forest management, and economic efficiency, national governments established programs for measuring and analyzing rainfall. In the U.S., this function was carried out by the U.S. Weather Bureau, which became the National Weather Service (NWS) in 1970. The Weather Bureau conducted rainfall analyses that supported road building and the design of engineering structures such as sewers and dams. For example, since the late 19th century, civil engineers have utilized the so-called rational method (Kuichling, 1889) for roadway drainage design. A related method from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS; formerly Soil Conservation Service, SCS), known as the SCS Runoff Curve Number method (Mockus, 1972), can also be used. These methods rely on “design storms” of a known intensity for a given return period and duration. In the U.S., design storm intensities are derived using intensity-duration-frequency information similar to Figure 1 below, which is based on Weather Bureau Technical Paper-40 (Hershfield, 1961a). Typical return periods include 25, 50 or 100 years depending on the importance of the roadway. Even today, such rainfall analyses underpin the design of important structures such as detention basins, roadways, bridges, and dams, and these maps continue to be periodically updated by the NWS (e.g., Bonnin et al. 2006).

The focus of this chapter is progress in hydrology for the last 100 years. As with any effort to track the progress of a field over a century, it is not quite possible to document all the advancements made across all sub-disciplines. However, to make our review scoped appropriately for this

American Meteorological Society (AMS) Monograph and its readers, we provide greater focus on the theoretical underpinnings of surface processes, the atmosphere above and the interactions within the land-atmosphere interface. During the last 100 years, we have seen a marked transition that has improved practical applications of hydrology through fundamental advancements in hydrologic science, including contributions to Earth system science (Sivapalan, 2017). As first described in Chow (1964) and later proposed and extended by Sivapalan and Blöschl (2017) and shown in Figure 2, hydrology first progressed through the Empirical Era (1910-1930), to the Rationalization Era (1930-1950), to the Systems Era (1950-1970). These periods were followed by the Process Era (1970-1990), the Geosciences Era (1990-2010), and finally by the current Co-evolution Era (2010-2030). As noted in the figure, the foundations of networks, experimental basins, operations research, high performance computing, remote sensing, and big data have advanced hydrological understanding. At the time of the founding of the AMS, there was a single journal—Monthly Weather Review (MWR)—that served as an outlet for hydrologic science in the AMS community. In the first several decades of this period (1919-1959, Empirical to Rationalization Eras), MWR articles reflect the emergence of quantitative hydrology from empirical observation (as will be discussed in Section 2 below). Examples include discussions of floods (Henry, 1919; Henry 1928; Nagler, 1933), rainfall-runoff relationships (Fischer, 1919; Shuman, 1929; Zoch, 1934), and even the potential of seasonal rainfall prediction based on snow pack (Monson, 1934). Later, MWR articles (1960-2000; Systems to Process and Geosciences Eras) became less focused on basic hydrology, partly due to the emergence of hydrology journals including the Hydrological Sciences Journal (established in 1956), the Journal of Hydrology (established in 1963), and AGU’s Water Resources Research (WRR; established in March 1965). Another factor in the change in hydrology focus for MWR articles in this period is related to the establishment of the Journal of Applied Meteorology (JAM) in 1962, along with the emergence of hydrometeorology and hydroclimatology, which culminated with the introduction of the Journal of Hydrometeorology in 2000. Classic examples from MWR include Rasmusson's (1967; 1968) water vapor budgets, Lettau's (1969) evaporation climatonomy, Manabe et al.'s (1969) bucket model and Priestley and Taylor's (1972) evaporation formulation. Examples from JAM include the albedo model of Idso et al. (1975), Adler and Negri's (1988) infrared rainfall technique, Nemani et al.'s (1989) satellite-based surface resistance methodology, Dorman and Sellers (1989) Simple Biosphere Model parameter climatologies, Beljaars and Holtslag's (1991) land surface flux parameterization, Daly et al.'s (1994) topography-based precipitation analysis methodology, and Hsu et al.'s (1997) neural network based satellite precipitation estimation.

An article in WRR's recent 50th anniversary issue by Rajaram et al. (2015) identified the topics covered by the top 10 most highly cited papers of each decade since 1965. These topics mirrored the evolution of topics in MWR and JAM, from infiltration and evapotranspiration formulations, to land surface hydroclimatological models and data assimilation. In addition to the evolution of scientific topics, progress in hydrology during this period is marked by the establishment of Hydrology as a science rather than an "application" (e.g., Klemeš, 1988). The so-called Eagleson "Blue Book" (National Research Council, 1991; Eagleson, 1991) was a bellwether moment in hydrology, because it helped define hydrology as a distinct geoscience, and recommended the establishment of research and educational programs in hydrology, hence the so-called "Geosciences Era" from 1990-2010 (Sivapalan and Blöschl, 2017).

Since JHM was initiated in 2000, the growth and impact of hydrologic research both within the AMS community (e.g., Figure 3), and overall (Clark and Hanson, 2017) has been substantial. In this monograph chapter, we will review progress in hydrology for the last 100 years, including theory, observations, and forecasting. Major themes such as the emergence of global hydrology, coupled land-atmosphere modeling including hydrometeorology and hydroclimatology, dynamical hydrologic prediction, and water resources management and water security will be reviewed. Finally, we look forward with a discussion of future directions.

2 The Evolution of Hydrologic Understanding

As noted in Chapter 1 of the Handbook of Hydrology (Maidment, 1993), quantitative hydrology emerged in the 1850s with Mulvaney's (1851) time of concentration concept, and Darcy's (1856) law of groundwater flow. Surface water flow equations developed shortly thereafter by Saint-Venant (1871) and Manning (1891) underpin today's routing schemes. Infiltration models from Green and Ampt (1911) to Horton (1933) provide a physical basis for rainfall-runoff modeling that further advanced hydrologic science. In this section, we focus on advances in hydrologic theory over the past 100 years in 6 key areas: (1) precipitation; (2) evaporation; (3) infiltration and soil water movement; (4) groundwater; (5) streamflow and routing; and (6) hydrogeomorphology.

a. Precipitation

In the previous section, we described widely-used concepts such as precipitation intensity-duration-frequency curves for engineering design for structures such as roadways, sewers and dams. Accordingly, from the hydrology perspective, key theoretical developments with respect to precipitation were initially focused on estimating precipitation extremes, including statistical techniques and the design of rainfall measurement networks. The reader is referred to Chapter 12 of this Monograph for a more detailed treatment of advances in observing and modeling mesoscale precipitation processes. In this section, we focus on advances in precipitation estimation for hydrometeorological and hydroclimatological applications.

A fundamental concept in the estimation of rainfall intensities for high-hazard structures such as dams is the Probable Maximum Precipitation (PMP; Hershfield, 1961b; WMO, 2009) which is defined as “theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year.” The general procedure for calculating PMP relies on estimating maximum precipitable water, convergence rate, and vertical motion, and there are numerous reports available produced by the NWS from 1963-1999 that provide PMP estimates for the U.S. (http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html). Unfortunately, these efforts have been discontinued due to lack of funding. Despite this, PMP estimation is still an active area of research, and recent publications suggest that PMPs are changing along with climate (Kunkel et al. 2013; Chen et al. 2017).

Around the same time, the design of precipitation networks became a focus, including Dawdy and Langbein (1960), Peck and Brown (1962), and Peck (1980), who recognized the role of topography in areal precipitation estimation. Rodríguez-Iturbe and Mejía (1974a,b) further studied point-area relationships and rainfall network design. These works ultimately led to the highly-cited work of Daly et al. (1994), who use observed precipitation and temperature gradients with topography to provide gridded precipitation products for CONUS.

Beyond these studies, major advances in the simulation of precipitation time series as spatially correlated random fields led to further advancements in stochastic hydrology. Understanding the space-time structure of precipitation allowed hydrologists to simulate precipitation over areas of interest, such as watersheds or river basins. Examples include Huff and Changnon (1964); Amorocho and Wu, (1977); Waymire, Gupta and Rodriquez-Iturbe (1984); Georgakakos and Bras, (1984); Eagleson et al. (1987); Foufoula-Georgiou and Lettenmaier (1987); Sivapalan and Wood (1987) and Foufoula-Georgiou (1989). This work complemented studies that identified the fractal and ultimately multiscaling structure of precipitation (e.g., Zawadzki, 1987).

b. Evapotranspiration

Evapotranspiration (ET) represents the combination of open water, bare soil, and canopy surface evaporation and transpiration. Theoretically, ET represents a turbulent flux of water vapor from the earth's surface to the atmosphere resulting from the phase change of liquid water. This phase change means that ET is coupled to the surface energy balance via the latent heat of vaporization, and therefore the transfer of energy from the surface to the atmosphere due to evapotranspiration is also referred to as the latent heat flux. If the phase change is from solid to vapor, then this energy transfer must also include the latent heat of sublimation. ET can be estimated as the product of the kinematic turbulent flux of water vapor (w'q'), and the density of air. This is the concept behind the eddy covariance measurement technique, as will be discussed further in section 3.f. below.

Given that ET is a dominant term in the terrestrial water budget, there have been many efforts designed to estimate this term with limited meteorological information. An important concept in ET estimation is that of potential evaporation (PE), which is defined as "the quantity of water evaporated per unit area, per unit time from an idealized, extensive free water surface under existing atmospheric conditions" (Maidment, 1993, p. 4.2). This concept effectively represents atmospheric "evaporative demand". A closely related concept is that of reference crop ET (denoted ETo), which is the rate of ET from an idealized grass crop with a fixed height, albedo, and surface resistance. In order to obtain actual ET from potential or reference ET, PE or ETo are multiplied by a series of coefficients representing specific crops and stress factors (Allen et al. 1998; Doorenbos and Pruitt, 1977).

In general, the methods for PE estimation can be classified as (1) temperature-dependent methods or (2) combination methods. The original, and still widely-used temperature dependent method was developed by Thornthwaite (1948). This method has been shown by numerous authors to overestimate the sensitivity to air temperature changes (e.g., Milly and Dunne, 2016), and alternative temperature-based methods have been shown to behave more like combination methods (e.g., Blaney and Criddle, 1950; Hargreaves and Samani, 1985).

The foundation of combination methods is Penman (1948), who combined the energy balance approach with an aerodynamic approach to derive an estimate of ETo based on an implicit assumption of measurement height and roughness length (Thom and Oliver, 1977). Monteith (1965) generalized the Penman equation, by calculating leaf resistances in series with the aerodynamic resistance employed by Penman. This led to a generalized form of the reference crop ETo equation now known as the Penman-Monteith equation. Priestley and Taylor (1972) found that ETo could be approximated quite accurately using a simplified form of Penman's equation requiring only the available energy (=net radiation minus ground heat flux) and a coefficient that changes depending on humid or arid climates, as defined by relative humidity. The most general form of the Penman-Monteith equation utilizes both aerodynamic and canopy resistances in series, where the canopy resistance (or its inverse, the conductance) can be calculated using a Jarvis (1976) approach, which depends on both leaf area and soil moisture (e.g., Lhomme et al. 1998). A comprehensive summary of ET theory and methods is given in Brutsaert (1982) and Dolman (2005).

Modern approaches to estimating actual ET fall into three categories: energy balance (e.g., Su et al. 2009; Anderson et al. 1997; 2011), combination (e.g., Penman-Monteith or Shuttleworth-Wallace, 1985) and complementary approaches (e.g., Bouchet, 1963), or combinations thereof (e.g., Mallick et al. 2013), and the choice and performance depends primarily on the availability of required data (Mueller et al. 2013). Most modern land surface models used in climate models (as will be discussed in Section 6 below) calculate ET using a Jarvis-based energy balance approach or a coupled photosynthesis-canopy conductance energy balance approach (Ball et al. 1987), as discussed in the review by Wang and Dickinson (2012).

c. *Infiltration and Soil Water Movement*

In the Empirical era, infiltration estimation was primarily focused on estimating losses for runoff, and this led to the work of Green and Ampt (1911), which was later shown to be consistent with theory and observations, with some updates to account for antecedent moisture conditions (Mein and Larson, 1973). It was also shown to be an expression of the Time Condensation Approximation (TCA; Sivapalan and Milly, 1989). Horton (1933) further investigated infiltration, and found that a time-varying infiltration capacity can be used to better estimate infiltration excess runoff than the so-called “rational method”. In Horton’s work, estimating “effective rainfall”, which is the infiltrated water available to plants, was another major objective. Philip (1957) derived a series solution for infiltration into a vertical, semi-infinite homogeneous soil surface, and since that time, this approach has largely been replaced by numerical solution of the governing equation for soil water movement as described below.

Richards (1931) derived an equation for capillary conduction of liquids through porous mediums, which combines Darcy’s law applied to unsaturated media with the continuity equation. The “Richards equation” is the foundation for predicting both infiltration and soil water movement, and soil moisture specifically. There are a number of works geared towards the proper form of this equation for numerical solutions (e.g., Celia et al. 1990; Zeng and Decker, 2009), in addition to various functional forms for the required soil water characteristic curves, which are nonlinear, hysteretic, and a function of soil texture (e.g., Brooks and Corey, 1964; Clapp and Hornberger, 1978; Rawls et al. 1982; van Genuchten, 1980). The Richards equation is the basis for many of today’s hydrological and land surface models (e.g., Downer and Ogden, 2004; Lawrence et al. 2011), although there are still challenges to its application and solution (Farthing and Ogden, 2017).

d. Groundwater

As with other aspects of the hydrological cycle, early efforts to characterize groundwater focused on mapping groundwater resources. The US Geological Survey (USGS) was a pioneer in this area, and the foundational work of Meinzer (1923) defined groundwater provinces as well as the basic principles of groundwater occurrence and movement. As with soil water movement, groundwater flow in saturated porous media is governed by Darcy's (1856) law. Combining this constitutive relation with the continuity equation led to key theoretical developments in describing groundwater motion, e.g., Theis (1935), Hubbert (1940), Jacob (1940), and Hantush and Jacob (1955). Texts such as Bear (1972) and Freeze and Cherry (1979) provide more in-depth treatments of the topic. A breakthrough in the recognition of the role of groundwater in runoff generation came from Dunne et al. (1975), who showed that saturated areas intersecting the surface produced instantaneous runoff known as "saturation excess" in contrast to the Hortonian "infiltration excess" runoff produced when rainfall exceeds the infiltration capacity. This led to the observation that these saturated areas could be approximately represented via a topography-based drainage index, which led to to the so-called TOPMODEL concept for parameterizing saturated areas (Beven and Kirkby, 1979). Later, Yeh (1986) formalized inverse approaches for identifying parameters for groundwater hydrology that are now commonly used in groundwater modeling.

These theoretical developments were later translated into numerical models, the most prevalent being the USGS MODFLOW (Trescott et al. 1980; McDonald and Harbaugh, 2003). In the last 20 years, there has been a push to include representations of groundwater flow in land surface models, ranging from simple treatments based on the TOPMODEL concept (e.g., Famiglietti and

Wood, 1994; Koster et al. 2000a; Niu et al. 2007) to more complex treatments based on groundwater flow models (e.g., Maxwell and Miller, 2005; Fan et al. 2007; Miguez-Macho et al, 2007).

e. Streamflow and Routing

The theory of surface water flow has been well-known since Saint-Venant (1871) derived the shallow water equations (also known as the Saint-Venant equations) based on the conservation of mass and momentum (i.e. the Navier-Stokes equations). Depending on which terms in the Saint-Venant equations are retained, the equations may be reduced to "kinematic wave" (e.g., Lighthill and Whitham, 1955; Feldman, 2000; Getirana et al. 2012) or "diffusion wave" approximations (e.g., Julien et al. 1995). The full 1-D equations are known as "dynamic wave" (e.g., Brunner, 2016), and are computationally intensive to solve, and cost-accuracy tradeoffs remain even for approximations to these equations (Getirana et al. 2017). The velocity of flow in open channels was described by Manning (1891), who re-developed an earlier relationship by Gauckler (Hager, 2001) in which velocity is related to slope, roughness and cross sectional area. Combining the velocity formulation with the Saint-Venant equations allows for the prediction of streamflow in open channels as well as overland flow on hillslopes (e.g., Chow, 1959).

Routing refers to the prediction of changes in the height (stage) and volumetric flow rate (discharge) of water (i.e. the hydrograph) as it moves over a hillslope or through a river channel or a reservoir (Woolhiser and Liggett, 1967). Hydraulic or distributed routing refers to solving both the continuity and momentum equations, while hydrologic or lumped routing refers to the continuity equation alone. One of the first approximate techniques to transform rainfall as a runoff response was Sherman's (1932) unit hydrograph. This technique allows the computation of a hydrograph by convolving the excess rainfall with a response function that could be derived for each watershed (e.g., Dooge, 1959). This approach is still in use in engineering hydrology (e.g., Feldman, 2000), although the most prevalent hydrologic routing technique is the Muskingum (McCarthy, 1940) or its extension, the Muskingum-Cunge (Cunge, 1969; Todini, 2007) method.

In addition to overland flow routing described above, there is also the concept of subsurface flow routing, which is an approximation to unsaturated and saturated groundwater flow (as described above). As discussed by Tague and Band (2001), the TOPMODEL (Beven and Kirkby, 1979) approach can be described as an "implicit" routing approach in contrast to "explicit" approaches such as Wigmosta et al. (1994). The developing National Water Model, based on the WRF-Hydro system (Gochis et al. 2015), currently uses a configuration that includes explicit subsurface routing, diffusive wave surface routing and Muskingum-Cunge channel routing.

f. Hydrogeomorphology

Hydrogeomorphology "focuses on the interaction and linkage of hydrologic processes with landforms or earth materials and the interaction of geomorphic processes with surface and subsurface water in temporal and spatial dimensions" (Sidle and Onda, 2004). Eminent hydrologists including Horton, Langbein (Dooge, 1996), Freeze and Harlan (1969), Dooge (1973), Beven and Kirkby (1979) have clearly recognized the linkages between the landscape and hydrologic processes. During the so-called "systems era" (1950-1970), the full integration of hydrologic theories and processes was explored and led to the Freeze and Harlan "blueprint" for hydrologic modeling, as discussed recently by Clark et al. (2017). As we progressed to the process era (1970-1990), hydrogeomorphological work focused on the search for universal laws (Dooge, 1986), the linkages between climate, soil and vegetation (Eagleson, 1978a-g), and scaling and similarity (Wood et al. 1988; Blöschl and Sivapalan, 1995).

As discussed in Peters-Lidard et al. (2017), one outcome of this era is the Representative Elementary Area (REA) concept (Wood et al. 1988; Fan and Bras, 1995), which found that the rainfall-runoff process behaved in a much simpler manner at the roughly 1 square kilometer scale. Later extensions to the concept include the Representative Elementary Watershed (REW) introduced by Reggiani et al. (1998, 1999, 2000, 2001) and the Representative Hillslope (RH; Troch et al. 2003; Berne et al. 2005; Hazenberg et al. 2015). The REA/REW approach is conceptually similar to Reynolds averaging, and assumes that the physics are known at the smallest scale considered (e.g. Miller and Miller, 1956). In another parallel, fluxes at the boundaries of model control volumes require parameterization (i.e. “closure”), with assumptions that are typically ad-hoc, and may include sub-grid probability distributions, scale-aware parameters, or new flux parameterizations.

Explicit “Newtonian” modeling of hillslopes at “hyper-resolutions” (Wood et al. 2011), or with clustered 2-D simulations (e.g., the HydroBlocks of Chaney et al. 2016), may render the REA/REW approach obsolete, although hydrogeomorphological connections continue to be explored. For example, Maxwell and Condon (2016), found that the interplay of water table depths with rooting depths along a given hillslope exerts different controls on evaporation and transpiration, linking the water table dynamics with the land surface energy balance. Further, the concept of catchment co-evolution and “Darwinian” hydrology (Sivapalan, 2005; McDonnell et al. 2007, Thompson et al. 2011; Harman and Troch, 2014) has extended scale and similarity concepts to synthesize catchments across scales, places and processes, ushering in the "Co-evolution Era".

3 Advances in Hydrologic Observations

Moving from point to areal estimates of hydrologic states and fluxes has revolutionized hydrologic science. Advances in precipitation estimation from gauges to radars to satellites, combined with similar advances in observing snow packs, soil moisture, terrestrial water storage, evapotranspiration, and stream stage and discharge, have enabled continental and global-scale hydrology. Famiglietti et al. (2015) provide an overview of the advantages of satellite based observation, including global coverage, near-continuity across space and time, and consistency of measurements from a given instrument. Taking the other side of the argument, Fekete et al. (2015) describe the shortcomings and dangers of over-reliance on remote sensing, including errors associated with mis-calibration of remote sensing retrieval algorithms, coarse spatial resolution relative to in situ measurements, inconsistencies associated with technology/instrument changes, and termination of long term in situ measurement locations incorrectly perceived to have been made obsolete by remote sensing.

a. Precipitation

Rain gauges, disdrometers and radars have long been conceptualized as the data reference for precipitation studies. The use of standardized rain gauges has been documented as early as the 15th century in Korea, so it is not surprising that for a long time in history they have been considered as indispensable for precipitation science (Tapiador et al. 2011). In fact, rain gauges are still considered the privileged source of reference data for precipitation estimates as they provide a direct physical record of the hydrometeors (cf. Kucera et al. 2013). Most of the global datasets of precipitation such as the Global Precipitation Climatology Project (GPCP; Adler et al. 2003, 2012, 2017), or the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997; Xie et al. 2003) include them in one way or another, and they are still used to calibrate and tune climate models. The same applies to other climate data records from multi-satellite observations (Ashouri et al. 2015). Disdrometers—modern instruments that estimate not only the total precipitation but also the drop size distribution (DSD)—are also becoming increasingly important part of ground instrumentation systems. Disdrometers are direct in that they respond to individual drops, but they have a fairly small sampling area (tens of square centimeters), which affects the representativeness of the measurements (Tapiador et al. 2017).

In contrast, ground-based radars sample a large volume but provide an estimate of the precipitation based on the backscattered echo, an indirect observation which relates to total rainfall through the DSD. In recent times, exploiting the radar transmit/receive polarization state has enhanced radar capabilities by discriminating the phase of the hydrometeors (Bringi et al. 1990). These three ground observations of precipitation (gauges, disdrometers and radars) were the primary input for hydrologic models for many years.

However, beginning with the inception of operational passive microwave imagery onboard the operational Defense Meteorological Satellite Program (DMSP) low Earth-orbiting (LEO) satellites in 1987, and continuing with the joint NASA-JAXA Tropical Rainfall Measuring Mission (TRMM) in 1997 (Simpson et al. 1988), a shift towards a blended or merged use of both ground-and satellite-based precipitation estimates was initiated (Adler et. al. 2000; Huffman et al. 2007, Joyce et al. 2004, Behrangi et al. 2009; Kidd and Huffman 2011). With microwave-based precipitation observations onboard multiple LEO satellites, complemented by the fast-refresh capabilities (30-minutes or less) of operational geostationary visible and infrared imaging sensors, improved global precipitation was enabled at spatial and temporal scales relevant to hydrological models and applications (Hossain and Lettenmaier, 2006; Nguyen et al. 2017; Nguyen et al. 2018). TRMM demonstrated the first spaceborne precipitation radar (Iguchi et. al., 2000), and algorithms that fused passive and active measurements for global precipitation estimation over tropical and subtropical regions (Kummerow et. al., 2000). TRMM was key to improving our understanding of the water cycle and the role of latent heat in the Earth system (Tao et. al., 2016). The role of TRMM in improving our knowledge of the structure (and thus of the physics) of hurricanes cannot be underestimated (Hawkins and Velden, 2011).

More extensive global coverage at higher latitudes (i.e., poleward of TRMM's limited 35-degree latitude coverage) culminated with the launch of the joint NASA-JAXA Global Precipitation Measurement (GPM) core observatory in 2014 (Skofronick-Jackson et al. 2017). GPM's dual frequency precipitation radar and higher orbit inclination expands the measurements to more over-land regions where much of the water cycle is driven by frozen precipitation processes (Houze et. al., 2017).

Regarding the future of precipitation estimation from space, the direction in the US points to small systems such as Cubesats (Peral et al. 2018), with an emphasis on understanding the interplay between aerosols and precipitation; aqueous chemistry; and a better understanding of convection.

Such topics are those favored by the National Academies Decadal Survey of Earth Sciences and Applications from Space (2018), and therefore will be likely the drivers of future missions.

b. *Snowfall*

Quantification of frozen precipitation has been especially difficult in the past. Indeed, instrumentation designed to remotely sense snowfall water equivalent (SWE) rates, for example, be it via weighing gauge, radar, or disdrometer have all addressed the challenges to deal with maintenance, calibration, point-to-area representativeness, measurement error, wind, etc., in addition to the irregular shapes, sizes, and bulk density of snowfall (Tapiador et al. 2012)

There are ways to retrieve SWE rates over larger areas using combinations of polarimetric radar, disdrometer and weighing gauge data (Brandes et al. 2007; Huang et al. 2010), however doing so is tedious and case specific (Tapiador et al. 2012). The advent of the GPM core observatory, with its enhanced capabilities over TRMM and the ability to measure the solid phase over the whole planet has opened a new phase for hydrology.

c. *Snowpack*

Observations of snowpack properties, such as Snow Covered Area (SCA)/Snow Cover Extent (SCE), snow depth and Snow Water Equivalent (SWE), prove challenging due to the considerable variability at fine spatial scales (e.g., Blöschl, 1999; Erickson et al. 2005; Dozier et al. 2016). Ground-based measurement of SCA is labor-intensive, although tower-mounted imaging is still a useful verification technique, and new approaches such as low-cost temperature sensors can be used to monitor seasonal SCA (Lundquist and Lott, 2010). Remote sensing of SCA was among the first applications of satellite data (as discussed in the review by Lettenmaier et al. 2015), and today, the spatial and temporal evolution of SCA is monitored with multiple satellites, including 30-meter resolution Landsat (Rosenthal and Dozier, 1996), 500-m resolution Moderate Resolution Imaging Spectroradiometer (MODIS; Hall et al. 2002; Painter et al. 2009), and 1000-m resolution Advanced Very High Resolution Radiometer (AVHRR; Ramsay, 1998; Romanov et al. 2000). These datasets have been used to construct a Climate Data Record of northern hemisphere SCA from 1966-present (Estilow et al. 2015).

Ground-based observations of snow depth can be obtained through intensive depth probe sampling (Elder et al. 1991), photographs (Tappeiner et al. 2001; König and Sturm, 1998), and snow pits (e.g., Cline et al, 2004) along with ground-based and airborne radar (Machguth et al. 2006) and lidar (Deems et al. 2013). Ground-based measurement of SWE is done through snow pillows with pressure transducers (Beaumont, 1965). Routine airborne SWE monitoring is conducted over CONUS using gamma ray sensing (Carroll and Carroll, 1989; Carroll, 2001). Satellite-based monitoring of snow depth has been demonstrated with passive microwave sensors (Chang et al. 1987; Kelly et al. 2003; Kelly, 2009), despite issues of signal saturation for SWE>200mm and loss of signal in heavily forested areas (Vuyovich et al. 2014). To overcome some of the limitations of the passive microwave approach, the community generally favors an integrated approach among multiple satellite sensors (Frei et al. 2012). Alternatives that have been shown to work well in mountainous regions such as lidar (Painter et al. 2016) and Ka- and Ku-band radar (Hedrick et al. 2015; Liao et al. 2016) are recommended in the most recent National Academies Decadal Survey of Earth Sciences and Applications from Space (National Academies of Sciences Engineering and Medicine, 2018).

d. Soil moisture

Soil moisture is significant in its roles as an atmospheric lower boundary condition, a regulator of near-surface temperature, evapotranspiration, and photosynthesis, an influence on flash flooding and surface runoff, an indicator of wetness conditions and drought and as the water available to shallow rooted plants. As discussed in Walker et al. (2004), Robinson et al. (2008), and Peng et al, (2017), there are many techniques to measure soil moisture with ground instruments, including gravimetric methods (e.g., Vinnikov and Yeserkepova, 1991), time domain reflectometry (e.g., Robinson et al. 2003), capacitance sensors (e.g., Bogena et al. 2007), neutron probes (e.g., Hollinger and Isard, 1994), electrical resistivity measurements (e.g., Samouëlian et al. 2005), heat pulse sensors (e.g., Valente et al. 2006), and fiber optic sensors (e.g., Garrido et al. 1999). One of the first efforts to compile ground-based soil moisture into a global database was Robock et al. (2000). More recently, this effort has been expanded by Dorigo et al. (2011), and over the U.S. there is a comprehensive data collection effort described by Quiring et al. (2016). As described by Crow et al. (2012), several in situ networks have been established and expanded with the goal to evaluate satellite-based soil moisture products. While these networks are primarily focused on in situ sensors, an exciting development for measuring intermediate-scale soil moisture is via cosmic-ray neutrons (Zreda et al. 2008). This has led to the development of the Cosmic-ray Soil Moisture Observing System (COSMOS) soil moisture network, which has expanded from the US to provide some international coverage.

Remote sensing of soil moisture is possible because soil moisture changes the surface emissivity and backscattering properties in microwave frequencies (Schmugge et al. 1974; Njoku and Kong, 1977; Dobson et al. 1985). Surface roughness, vegetation and the presence of rainfall confound the retrieval of soil moisture. Both active and passive microwave respond to soil moisture signals from a shallow surface layer, with the 1.4 GHz (L-band) penetrating to about 5 cm, and less at higher frequencies. Soil moisture products have been generated from numerous sensors, from the Scanning Multichannel Microwave Radiometer (SMMR) sensor on board Nimbus (launched in 1978) to the most recent ESA Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al. 2016) launched in 2009, and the NASA Soil Moisture Active and Passive (SMAP) mission (Entekhabi et al. 2010) launched in 2015. Retrieval algorithms vary from the SMAP single and dual channel algorithms (O'Neill et al. 2015) and Land Parameter Retrieval Model (LPRM) (Owe et al. 2001; Owe et al. 2008), to the L-band Microwave Emission of the Biosphere (L-MEB) model (Wigneron et al. 2003) of SMOS. Radiometers and scatterometers have been shown to provide highly correlated and somewhat complementary information (de Jeu et al. 2008), and radiometer algorithm performance has been shown to depend strongly on vegetation and roughness parameterizations (Mladenova et al. 2014). Recent attention has focused on providing both long time series soil moisture data records (Dorigo et al. 2017) and fine spatial scale soil moisture information (Peng et al. 2017) from multiple platforms using a variety of approaches. These approaches are increasing the relevance of remotely sensed soil moisture for drought assessment, agriculture, and vadose-zone hydrology (Mohanty et al. 2017).

e. Terrestrial water storage

Terrestrial water storage refers to the all the water stored in and on a column of land, i.e., the sum of groundwater, soil moisture, surface waters, snow, ice, and wet biomass. It is the freshwater that enables life on land. It is also one of the four terms in the terrestrial water budget, i.e.,

$$dS = P - ET - Q \qquad (1)$$

where dS is the change in terrestrial water storage, P is precipitation, ET is evapotranspiration, and Q is runoff from a given study area. Defining that study area as a watershed, river basin, or other closed hydrologic unit facilitates the application of equation 1. Of the four terms, dS and ET are the most difficult to measure, and over the years many researchers have chosen to assume that dS is negligible in order to close the water budget or to infer ET – an increasingly dubious assumption as the study period shortens. Mintz and Serafini (1992) recognized the importance of dS and were among the first to account for it in a water budget analysis. Nevertheless, due to the difficulty of obtaining coincident measurements of all the terrestrial water storage components, only a few studies payed serious attention to the left side of equation 1. In particular, Yeh et al. (1998) and Rodell and Famiglietti (2001) assessed variations in terrestrial water storage using in situ observations of groundwater, soil moisture, snow depth, and reservoir storage from Illinois. They showed that the interannual variations in groundwater and terrestrial water storage in Illinois were of the same order of magnitude as those of soil moisture, thereby casting doubt on studies that relied on the assumption of dS equaling zero over the course of an annual cycle. Despite advances in hydrogeophysics (Binley et al. 2015), direct measurement of this term has been most successful from the vantage point of space.

Our ability to measure terrestrial water storage changes from space is somewhat serendipitous. In the 1980s and 1990s, geodesists, who measure the precise shape of the Earth and its gravity field, had been searching for a way to improve space based gravity measurement. The first satellite dedicated to this purpose, Lageos, looked like a silver-colored ball; it was an uninstrumented, mirrored sphere used for laser ranging from Earth's surface. By measuring departures from its predicted orbit, the geodesists could map irregularities in Earth's static gravity field. Yoder et al. (1983) inferred that Lageos and other satellites were also sensitive to temporal variations in the gravity field caused by atmosphere and ocean circulations and the redistribution of water on the land. Geodesists proposed that in order to measure those orbital departures with enough precision to quantify mass changes with a useful degree of accuracy, the measurements would have to be made by another, co-orbiting satellite (Dickey et al. 1997). Thus was born the Gravity Recovery and Climate Experiment (GRACE) satellite mission, developed jointly by NASA and two German agencies. GRACE, which launched in 2002 and continued operating until 2017, used a K-band microwave system to measure the distance (~100-200 km) between two identical, co-orbiting satellites, with micron level precision. Over the course of each month, these measurements were used to produce a new map of Earth's gravity field that was accurate enough that month to month changes in terrestrial water storage could be estimated, after using ground based measurements and models to remove the effects of atmospheric and oceanic mass changes (Wahr et al. 1998; Tapley et al. 2004).

Hydrologists were slow to embrace GRACE due to its data being much different from anything they had previously seen. In particular, relative to other remote sensing measurements the spatial resolution of GRACE is extremely low – on the order of 150,000 km^2 at mid-latitudes (Rowlands et al. 2005; Swenson et al. 2006). GRACE only provided month to month changes in terrestrial water storage with a multi-month time lag, whereas most remote sensing systems provide instantaneous observations with latencies that range from a few hours to a week. Finally, GRACE provides no information on the vertical distribution of the observed terrestrial water storage changes, leaving it to hydrologists armed with auxiliary data and models to determine how much each of the water storage components contributed to an observed change. As a result of these unusual characteristics GRACE data have been misinterpreted and misused by researchers in numerous instances, which has caused others to dismiss GRACE entirely (e.g., Darama, 2014; Alley and Konikow, 2015; Sahoo et al. 2016).

Nevertheless, because satellite gravimetry is currently the only remote sensing technology able to discern changes in water stored below the first few centimeters of Earth's surface, GRACE caused a revolution in water budget hydrology. Among the highlights, GRACE enabled closure of the terrestrial water budget and estimation of evapotranspiration as a residual (Rodell et al, 2004; Swenson and Wahr, 2006; Rodell et al. 2011), determination of ice sheet mass changes (Luthcke et al. 2006; Velicogna and Wahr, 2005; 2006), ablation of major glacier systems (Tamisiea et al. 2005; Chen et al. 2007; Luthcke et al. 2008), estimation of groundwater storage changes (Rodell et al. 2007) and trends (Rodell et al. 2009; Richey et al. 2015), enhanced drought monitoring (Houborg et al. 2012; Thomas et al. 2014), effects of terrestrial water storage changes on sea level (Boening et al. 2012; Reager et al. 2016), and improved understanding of seasonal and interannual variability of and human impacts on the global, terrestrial water cycle (van Dijk et al. 2014; Humphrey et al. 2016; Rodell et al. 2018). By 2010 the importance of GRACE to multiple disciplines became so clear that NASA promoted the GRACE Follow On mission ahead of several other missions which had been recommended by the 2007 Decadal Survey in Earth Sciences (National Research Council, 2007). GRACE Follow On launched successfully on 22 May 2018. While it will provide only a small improvement in resolution and accuracy over GRACE, it will ensure continuity of the terrestrial water storage data record.

f. Evapotranspiration

Measuring actual evapotranspiration (ET) directly is difficult, and as discussed above, reviews of theory and methods can be found in Brutsaert (1982) and Dolman (2005). The original measurement techniques included evaporation pans and weighing lysimeters, and more recent approaches include energy balance/bowen ratio, eddy covariance, sap flow, isotopes, and fluorescence (e.g., Wilson et al. 2001; Shuttleworth, 2007). For a handy reference summarizing these techniques, see Shuttleworth (2008). Networks of flux stations (FLUXNET; Baldocchi et al. 2001) are now prevalent, and approaches to postprocess these observations to address the closure problem (e.g., Twine et al. 2000) are required for comparisons among different approaches. Further, because the spatial footprint or "fetch" of these ground-based measurements is limited, empirical "upscaling" approaches (e.g., Jung et al. 2009) are required to produce gridded observations for global hydroclimatological analysis (e.g., Jung et al. 2010).

Remote sensing of ET is based on a number of techniques that depend on temperature, as summarized by Kalma et al. (2008). Popular variants of these techniques include Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al. 1998), Surface Energy Balance System (SEBS; Su, 2002), Mapping Evapotranspiration with Internalized Calibration (METRIC; Allen et al. 2007), Simplified Surface Energy Balance (SSEB; Senay et al. 2011), Atmosphere-Land Exchange Inverse (ALEXI; Anderson et al. 2011). Other remote-sensing based methodologies augment the temperature signal with weather model data and vegetation information from MODIS to apply the Penman-Monteith approach (e.g., Mu et al. 2011), or augment the temperature signal with other remote sensing data, soil water, interception, and stress accounting and apply a Priestley-Taylor approach (e.g., Global Land surface Evaporation: the Amsterdam Methodology—GLEAM; Miralles et al. 2011; Martens et al. 2017). Vinukollu et al. (2011) provided the first ever moderate resolution estimates of ET on a global scale using only remote sensing based inputs. The recent GEWEX LandFlux project evaluated multiple global ET products, ranging from models to remotely sensed, and found that no single approach outperformed the other (e.g., McCabe et al. 2016).

g. Surface water stage and discharge

In traditional hydrology, discharge (streamflow) at a stream location is considered a functional integration of the various surface and sub-surface hydrologic processes that occur in the area draining through that point. Measurement of this hydrologic variable forms the cornerstone of calibration and validation of hydrologic models, development of flow routing schemes and assessment of flow forecasting skill. In more recent times, as process-based understanding improved in hydrology, the importance of streamflow as a relatively easy to measure descriptor (using stage discharge relationship) only increased further. This is because streamflow can also exhibit signatures of the mechanistic role played by land cover change (deforestation), land-surface interactions, surface-groundwater interactions, climate and weather change, drought and fluvial processes, and of course water management (see section 5).

Governments of the developed world have built extensive networks of river and stream gauges to track the flow (Hannah et al. 2011). For example, the Global Runoff Data Centre (GRDC) archives data from more than 9200 gauges worldwide, and the US Geological Survey (USGS) collects real-time streamflow data at nearly 10,000 locations within the United States. Such streamflow data records have played a vital role in the continued development of hydrologic, land-surface, climate and earth system models today.

A key limitation of conventional streamflow monitoring using stage discharge relationship is two-fold. First, such networks do not exist in developing countries of the world where most often there are no records of streamflow in rivers along the reach. Even if records were maintained, they are usually not shared openly as is the norm in developed countries (Hossain et al. 2014). Second, point-based stage monitoring of discharge is able to only capture the flow that passes through a one-dimensional point. Such measurements do not capture the two-dimensional exchange of water mass that can occur laterally, especially in wetlands, floodplains and braided rivers. In response to the first limitation, remote sensing community has been using satellite radar altimeters that were originally designed for ocean monitoring, to build a steady record of river heights (Birkett, 1998; Gao et al. 2012) and lake and reservoir elevations (Birkett et al. 2011). For both limitations, scientific community is now eagerly awaiting a proposed satellite mission, the Surface Water Ocean Topography (SWOT; Alsdorf et al. 2007), scheduled for launch in 2021, SWOT mission will provide the community with a more spatially distributed estimate of the flow in water bodies. With its global sampling from space of water elevation, its temporal change, and its spatial slope in fluvial environments, as well as across lakes, reservoirs, wetlands, and floodplains, (Biancamaria et al. 2016), SWOT measurements are expected to contribute to the further understanding of global scale hydrology.

4 Hydrologic Prediction Across Scales

a. Background

Hydrologic forecasting is one of the earliest applications of hydrologic theory, with deep roots in engineering, and particularly civil engineering in support of water systems management (Anderson and Burt, 1985). The need to anticipate and respond to hydrologic variability and the associated impacts on water uses and hazards has motivated the practice of hydrologic forecasting for much of the last century, and it is now a valuable part of operational services in most of the world's nations (Emerton et al, 2016; Adams and Pagano, 2016). Hydrologic forecasting applications most often target time scales from minutes to seasons, and focus not only on extreme events (droughts and floods), but also the entire spectrum of hydrologic variation in which even moderate departures from normal can affect water operations, management and planning across a broad range of sectors. Over the last century, scientific and technological advances have driven a steady growth in forecast capabilities, culminating in a modern landscape of forecasting in which the advent of high performance computing, broadband connectivity, and global high resolution geophysical datasets are transforming long-held traditional paradigms of operational prediction.

The concept of seamlessness (of models, data, methods and information products across space and time) is commonly touted as a development objective for hydrological forecasting systems as well as weather and climate forecasting systems (Wetterhall and Di Giuseppe, 2017; Hoskins, 2013). Yet for hydrologic forecasting, the strong foundation of engineering pragmatism coupled with limitations in methods, tools, data and scientific understanding have produced a fragmented, rapidly evolving variety of approaches and operational practices. Forecast products and services have traditionally been distinct along lead time scales and space scales – from the localized minutes-to-hours ahead phenomenon of flash flooding, to river stage and flow prediction at the river basin scale over periods of hours to days, to long range seasonal runoff and drought prediction which may span multiple river basins and focus on time-space-averaged predictands (e.g., seasonal snowmelt runoff). The dominant hydrologic processes, and the applicability of data, models and methods in each area are different, hence the operational pathways toward harnessing predictability have also differed, leading to multiple views on forecasting development strategies. For example, despite substantial progress in groundwater modeling (as noted above in Section 2d) and understanding interactions between surface water and groundwater (Brunner et al. 2017), groundwater level short-to-medium range forecasting relies to a greater extent on statistical and machine learning techniques (e.g., Daliakopoulos, et al. 2005) than on process based modeling (e.g., Prudhomme et al. 2017). Most surface-water hydrologic forecasting efforts supporting water management include only simplified representations of groundwater, if any.

Efforts to develop a spatially and temporally seamless paradigm over the last 15 years have yielded a proliferation of medium-to-high resolution applications of hydrologic models for continental to global-extent prediction – a trend resulting from the ready availability of high performance computing (HPC) resources, the ease of sharing models and methods, the accessibility of continental and global meteorological, hydrological, and extensive geophysical attributes datasets, including those derived from satellite-based remote sensing. This development has paralleled the migration of hydrology as a discipline taught in engineering schools towards an application of the geosciences, and a reframing of hydrologic forecasting from an engineering practice supporting water resources management toward the view of prediction as an Earth Science grand challenge. Today the fit-for-purpose traditional forecasting practice and the fledgling Earth Science prediction science co-exist, with the latter clearly on the rise. It is therefore timely to review the evolution of hydrologic modeling and forecasting for major phenomena, the better to understand the opportunities and challenges as new forecasting approaches arrive. In this section, we focus primarily on hydrometeorological prediction.

b. Seasonal forecasting

Hydrologic forecasts at seasonal scales (with multi-month lead times and predictand durations) predate the use of computers in hydrology (which began in the 1960s) by decades. The earliest seasonal operational forecasts, which are still today among the most economically valuable, were for peak seasonal runoff, as driven by phenomena such as snowmelt or monsoon season rainfall. Statistical methods have long been used to relate estimates of watershed variables including snowpack and accumulated moisture from rainfall (and in the last 25 years, climate indices and forecasts) to future runoff, often achieving high skill ($r^2 \sim 0.9$). In the US, the Department of Agriculture's SCS, now NRCS, began the practice in the mid-1930s, and was joined in 1944 by the NWS in issuing forecasts (Pagano et al, 2014; Helms et al, 2008). For most of their history, seasonal predictions have been probabilistic, providing a range of uncertainty, and currently help to inform water allocation decisions in major reservoir systems.

The development and adoption of computer-based conceptual catchment hydrology models in the late 1960s and early 1970s (e.g., Burnash, 1973) enabled a new 'dynamical' approach to seasonal hydrologic forecasting, now called 'Ensemble Streamflow Prediction' (ESP: Day, 1985; Wood et al, 2016). ESP involves running a real-time continuous hydrologic model simulation to estimate current watershed conditions, and then using these moisture states to initialize forward simulations based on a sample of historical weather sequences to project watershed conditions ahead into the forecast period. Different forms of ESP provide the central method used operationally in countries around the world, and ESP complements statistical volume forecast techniques by providing ensembles of streamflow sequences, often at the daily or sub-daily time step used in the hydrology model, from which a range of predicted variables of interest can be calculated (such as daily peak flow magnitude, timing and probabilities). Such streamflow sequences are commonly used to estimate runoff volume probabilities or input directly into reservoir operations models to calculate probabilities of future system states and outputs, given specific release policies (eg, Kistenmacher and Georgakakos, 2015).

In the early 2000s, ensemble seasonal hydrologic forecasting began to attract attention in the land surface modeling research community (Wood et al, 2002; Luo and Wood, 2008; Wood and Lettenmaier, 2006), leading to the development of LSM-based national, continental and global scale forecasting systems using ESP in addition to alternatives involving downscaled climate forecast model outputs (Duan et al, 2018). These large-domain LSM-based seasonal forecast systems, however, often lack several critical elements that increase skill in the traditional, operational lumped-model seasonal forecast issued from regional or small national centers. In particular, such centers perform comprehensive model calibration as well as data assimilation (mostly manual) to reduce and correct initial hydrologic state errors and thereby improve forecasts.

The practice of using parameter estimation and optimization to support the use of low-dimensional, agile conceptual models in gaged basins and for streamflow forecasting has spurred extensive research and practical successes, yielding widely-used techniques such as the Shuffled Complex Evolution (SCE; Duan et al, 1992) method, and leading to innovative multi-method packages (e.g., Mattot, 2017) and theoretical advancement toward joint parameter-state estimation approaches (e,g., Vrugt et al, 2006). Research into hydrologic model data assimilation has also provided a broad range of promising variational and ensemble techniques that have been shown in watershed-scale research applications to benefit not only simulation but also forecasting (Liu et al. 2012). These parameter estimation and DA practices remain less developed and effective for large-domain, regional to national scale LSM-based hydrologic prediction systems. This is due in large part on the inability of such methods in large-domain applications to rely directly on watershed observations such as gaged streamflow, versus on remotely sensed hydrologic variables such as soil moisture or snow cover. Regional parameters, may be estimated through schemes that either assign or calibrate relationships between terrain attributes and model parameters (e.g., Samaniego et al, 2010), or leverage similarity concepts or proximity to transfer parameter values estimated in well-gaged locations to ungaged locations (Wagener and Wheater, 200). Both techniques are critical important to the success of large-domain hydrologic forecasting, and are active areas of current research.

The heightened profile of seasonal hydrologic prediction in a research context has also spurred a new research thrust into quantifying seasonal hydrologic predictability and frameworks for the attribution of prediction skill to sources including initial hydrologic conditions (IHCs; primarily soil moisture and snow water equivalent) and future meteorological variability (Wood and Lettenmaier, 2008; Paiva et al, 2012; Mahanama et al, 2012; Wood et al, 2016). The strong role of IHCs in seasonal forecast skill argues that continued development of watershed modeling, observational monitoring and data assimilation is critically important. To enhance skill at longer lead times and for seasons in which the role of climate variability is large, however, sub-seasonal to seasonal climate forecasting inputs for hydrologic prediction offer a compelling area of investigation (see Wetterhall et al, 2016).

c. *River Flood forecasting*

Modern river flood forecasting traces back to the development and application of computer-based watershed models in the late 1960s and 1970s (e.g., Crawford and Linsley, 1966), and the techniques employed reflect the engineering heritage as well as limitations of the early decades of computer use. The capability began with discrete event forecasting based on relatively simple, empirical or statistical models, the earliest of which were essentially graphical in nature -- capturing observable relationships between rainfall, soil wetness, and future runoff for short lead times. Early techniques such as the use of antecedent precipitation index (API) models (Fedora and Beschta, 1989; O'Connell and Clarke, 1981) still exist operationally in parts of the world today, but have for decades been superseded by forecasting based on continuous watershed models.

The same models and software systems that brought dynamical (model-based) methods to the seasonal forecast context were among those used in the continuous river flood context, including the NWS River Forecast System (Anderson, 1972), which centered on conceptual snow and soil moisture accounting models within a system providing broad array of analytical and interactive techniques, e.g., for model calibration, state updating and post-processing. Some national-scale operational forecasting capabilities in the US and elsewhere (Pechlivanidis et al, 2014; Emerton et al, 2016) still rely heavily on such continuous conceptual model-based approaches, run in regional or national river forecasting centers. The most common application of these models remains relatively low-dimensional, favoring lumped discretization of small watershed areas (on the order of 10-500 km^2), enabling manual effort to be applied for calibrating models and for updating their inputs, states, and outputs in real-time during the forecasting workflow.

With the strengthening connection of the operational forecasting to Earth Science, the vastly improved geophysical datasets described above and the rapid advances in computing resources, the last decade has seen an unprecedented expansion in the range and complexity of modeling approaches currently being implemented for river forecasting at short to medium ranges (out to several weeks). The development and deployment of distributed 'macroscale' (order 100 km^2 spatial resolution) hydrology models in the 2000s for continental and global scale domains as part of land data assimilation systems (LDAS; Mitchell et al, 2004; Rodell et al, 2004) was a notable step toward a broader convergence between parameterization approaches in watershed-scale hydrological models and global-scale land surface models (LSMs) used in coupled climate models and as initial conditions for NWP. These large-domain LSMs were operationalized in research and agency settings for monitoring and prediction applications (Wood and Lettenmaier, 2006; Thielen et al, 2009; Alfieri et al, 2013), adopting techniques such as ESP from traditional seasonal forecasting. At the watershed scale, high resolution distributed process-oriented models also were implemented for forecasting applications, primarily at a local scale (Westrick et al, 2002).

Today, traditional river flood forecasting using conceptual models is joined by two new major operational river forecasting paradigms that leverage scientific advances and technical strategies from the field of Earth System Modeling (ESM). One is the application of very high-resolution watershed models (order 100m horizontal resolution) for national to continental domains, incorporating explicit hydrologic vertical and lateral fluxes at the model grid scale. Such computational demanding modeling is enabled by HPC and code parallelization, in some cases resourcing 1000s of cores, and places a new emphasis on the need to resolve long-standing hydrologic modeling challenges. In particular, the vast increase in the distributed parameter space coupled with the cost of simulation has underscored the need for efficient parameter estimation and regionalization approaches. A recent example of such an approach is the NWS National Water Model (NWM; Figure 5), which produces distributed, deterministic river flood predictions and other hydrometeorological outputs for every 250m of the US (Salas et al, 2018).

A second major paradigm to emerge centers on the development and application of ensemble techniques for forecasting (Duan et al, 2018), using either conceptual or intermediate scale hydrologic models, with the objective of ‘Completing the Forecast’ (National Research Council, 2006) -- i.e., providing forecasts with uncertainty estimates that can be used for risk-based decision-making. In the last 15 years, ensemble prediction has made great strides in the US and internationally, facilitated in part by the international Hydrologic Ensemble Prediction Experiment (HEPEX; Schaake et al, 2007) launched in 2004. A key challenge in the ensemble prediction context is the provision of probabilistic forecasts that are as accurate (sharp) as possible while maintaining statistically reliable spread (uncertainty) (Werner et al, 2016). Ensemble river prediction systems now co-exist with traditional forecasting systems in a number of countries; examples include the US NWS Hydrologic Ensemble Forecast Service (HEFS; Demargne et al, 2014) and the European Flood Awareness System (EFAS; Thielen et al, 2009), which coordinates with national hydrometeorological services to provide forecast services across Europe.

d. Flash flood forecasting

Flash flooding is one of the most damaging water-related hazards, particularly from a human life standpoint (with over 100 lives lost per year), but for most of the last century and in many countries today, the responsibility for forecasting of flash floods has been carried out by meteorological rather than hydrological services. This organization follows from both the distributed nature of flash flooding, in that deadly torrents of water can be generated on small creeks and washes that were not explicitly modeled in traditional river flood prediction systems, and the fact that flash flooding is proximally driven (far more than river flooding) by meteorological events, rather than a combination of rainfall inputs and subsurface fluxes (eg baseflow, interflow). For decades, flash flood watches and warnings have been a central alert category of the NWS, but were undertaken by weather forecast offices (WFOs) rather than RFCs, and issuing products describing areas or regions of risk (polygons on a map), rather than explicit locations with a quantitative high flow forecast.

Such products were originally generated from meteorological forecast maps alone, and have steadily improved in the last four decades. Progress in several foundational scientific and technical areas have driven these advances. Rainfall monitoring has benefited from improvements in the quality of multi-sensor products and objective analysis techniques, and forecasting has leveraged higher resolution and more accurate NWP. Improved satellite-based description of terrain and landcover have enabled hyper-resolution digital elevation models (DEMs) and runoff routing schemes. Hydrologic simulation has evolved from lumped, conceptual models to the development and implementation of ever-finer resolution distributed hydrologic models (Wigmosta et al, 1994; Bierkens et al, 2015) that can make use of distributed meteorological inputs.

The first of such distributed hydrology models to be applied operationally on large domains were intermediate scale, as exemplified by the the 1/8th degree multi-agency National Land Data Assimilation System (NLDAS) project LSMs, beginning in 1998 (Mitchell et al, 2004) and the 4-km NWS Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM; Koren et al, 2004). At a finer resolution, the 1-km distributed NWS Flooded Locations and Simulated

Hydrographs (FLASH) system in 2012 also began providing 1-km, 5-minute channel estimates of flash flood risk, based on the percentiles of simulated and routed flow relative to a background climatology (Gourley et al, 2014). Since 2016, the 250-m National Water Model (NWM) has issued quantitative 0-2 day channel lead flow predictions for a channel network defined by the USGS NHDPlus hydrography dataset, which includes 2.7 million river reaches.

Flash flood forecasting has commonly taken the form of 'Flash Flood Guidance' (FFG; Carpenter et al, 1999; Georgakakos 2006), in which models -- initially lumped and more recently gridded -- are used to estimate the quantitative capacity of the soil to absorb rainfall, which when combined with estimates of observed and forecasted precipitation, characterizes flood risk. In the distributed model context, where local calibration of runoff is not possible, a 'threshold frequency' concept is applied in which modeled flows above a certain frequency threshold (e.g., 2 year return period) relative to past model simulations are indicative of flood risk (Reed et al, 2007). Currently both lumped and gridded FFG approaches inform operational flash flood watch and warning products, and the practice has been promoted for international adoption by the World Meteorological Organization (WMO).

The WFO areal alerts and the NWM data products represent the diversity of strategies for flash flood forecasting, from local assessment resulting from experts integrating hydrometeorological information, to the automated outputs of a very high resolution LSM. Globally, development is underway to create fine-resolution, real-time distributed flood risk maps with low latency by merging satellite-based estimates of land inundation, river level altimetry, NWP and global NWP model runoff, and even real-time social media streams (ie, Twitter alerts) (Westerhoff et al, 2013).

e. The realization of a hydrologic prediction science

The nascent applications of LSMs and complex watershed models in prediction applications have unleashed great scientific and pragmatic enthusiasm for a new era of Earth System prediction that includes hydrological fields as well as more common meteorological ones. Yet the ease at which data streams can be connected to models, generating real-time outputs that can be called ‘forecasts’, belies the substantial difficulty in producing not just distributed model output, but actionable, high quality predictions at the local scales required for water and emergency management. Myriad, long-standing scientific challenges in hydrologic modeling remain unsolved (Clark et al, 2017), and are compounded by technical challenges that arise particularly in the operational forecasting context. Operational river forecasters grapple with these challenges–e.g., erratic or degraded data streams, model deficiencies, model state and input uncertainties–on a daily basis, and have a deep, first-hand understanding of the adequacy of hydrological methods to overcome them. Welles et al. (2007) highlighted the role that objective verification measures should play in adopting forecast process improvements. Essential techniques include parameter estimation (or model calibration, e.g., Welles and Sorooshian (2008)), meteorological forecast downscaling and bias correction, hydrologic data assimilation, hydrologic forecast post-processing, and accounting for and integrating water management – all of which reduce errors in model predictions.

Fortunately, the gap between the Earth System prediction research community and the operational river forecasting community is narrowing. The view that current operational methods are ad hoc or (in the case of model calibration) theoretically unsound, a way of ‘getting the right answer for the wrong reasons’, is waning as the ESM community begins to understand the role of such methods and forecasting-related challenges are re-articulated in the language of science. For all the advances of the last decade, modern hydrological models run in a fully-automated, ‘over-the-loop’ paradigm, without effective, objective counterparts to traditional techniques described above, often still fail to generate outputs matching the actionable quality of those created by simpler models using traditional approaches (Smith et al, 2004; Reed et al, 2004; Smith et al. 2013; Beven et al, 2015). Today, national and global-scale hydrologic forecasting system implementations successfully reflect large-scale variability but do not bear scrutiny at the local watershed scale, where river flood impacts are most relevant. To make global scale approaches usable locally, the Earth System prediction research community must continue to pursue scientific understanding and methods to improve engineering-based techniques in three key areas: model parameter estimation, hydrologic data assimilation of observations of all types, and representing human impacts on the hydrologic cycle.

Fortunately, over the last 15 years, a shift in perspective is leading to greater integration of traditional communities of practice and land surface modeling research. The international, multi-agency HEPEX initiative has fostered collaboration between communities of hydrologic research and practice, and promoted the recognition of operational hydrologic prediction as a coherent scientific sub-discipline rather than an engineering activity. Research funding in the US and elsewhere has increasingly supported collaborations with operational entities, and sessions on applied hydrologic prediction in national and international scientific conferences have greatly expanded. As this integration between traditional operational and research communities grows, an improved understanding of tradeoffs and limitations in forecasting system components is beginning to lead to more informed choices as Earth System research strives to create next generation prediction systems that provide actionable information at local scales.

From a stakeholder perspective as well, the landscape of hydrological forecasting is changing dramatically. For most of the last century, for a given river location, at most one deterministic flood forecast was available from the regional forecast center, using a locally tailored conceptual watershed model. Today, multiple forecasts for a given US location can be viewed and downloaded, including one from the NWM and additional ensemble predictions from global forecasting systems run outside of the US. For some of these systems, the runoff is even extracted from the land surface models of coupled global models (e.g., NWP systems), rather than from offline LSMs (Gaborit et al, 2017). These developments are ushering in a hydrologic forecasting future that is marked by an expansion from local and regional forecasting approaches toward national, continental, and global scale hydrologic prediction systems, run in centralized over-the-loop modes.

Improvements in forecast quality will come through a range of advances: better earth system modeling (including coupled NWP and climate prediction) and creative, efficient solutions for representing space-time heterogeneity (e.g., Peters-Lidard et al, 2017); improved observational data through data fusion and assimilation of satellite-based observations as well as non-traditional observations from social media; the adoption of reliable uncertainty frameworks; and the use of increasingly sophisticated statistical techniques (e.g., deep learning) merged in hybrid frameworks with dynamical modeling. The overarching scientific and community challenge facing the field today is the need to connect local knowledge and information to large-domain approaches, and in turn to make national to global system predictions relevant locally. With greater integration of the entire hydrologic prediction community -- including those in research, in operations, and stakeholders -- this challenge can be surmounted.

5 The Emergence of Global Hydrology

a. Key Milestones

As people gained the ability to travel more quickly and routinely across continents and around the world in the 20th century, it was inevitable that they would come to recognize the global connectivity of Earth's physical processes and systems, including the water cycle. Voeikov (1884) and Murray (1887) had the foresight to assess worldwide, terrestrial precipitation, evaporation, and runoff well before global scale meteorological measurements began to be collected systematically. Murray's (1887) global terrestrial precipitation estimate is particularly impressive, being only about 5-10% larger than the average of estimates from the 2000s (Figure 6a). Fritzsche's (1906) global terrestrial precipitation estimate was even better, but most studies misestimated evapotranspiration and/or runoff until Lvovich's (1972) published values that remain very close to the most modern estimates. Brückner (1905) and Fritzsche (1906) provided the first global ocean precipitation and evaporation estimates. Amazingly, they were only about 10% below modern estimates (Figure 6b). Mather (1969) and Baumgartner and Reichel (1973; 1975) were the first to hit the mark with both ocean evaporation and precipitation, based on recent estimates. Baumgartner and Reichel's (1975) and Budyko and Sokolov's (1978) land and ocean flux estimates, with some updates from Chahine (1992) and Oki (1999), continued to be used as benchmarks until Oki and Kanae (2006) and Trenberth et al. (2007) delivered updated global water balance assessments.

A decade after Baumgartner and Reichel's (1975) comprehensive treatise on the global water balance, Eagleson (1986) announced the "Emergence of Global-Scale Hydrology" and evaluated the state of global hydrological modeling at that time. Chahine (1992) helped to establish the global hydrology community in his review paper on the hydrological cycle and its influence on climate, declaring that, "In the short span of about 10 years, the hydrological cycle has emerged as the centrepiece of the study of climate, but ... rather than fragmented studies in engineering, geography, meteorology and agricultural science, we need an integrated program of fundamental research and education in hydrological science." Other important milestones included Berner and Berner's (1987) thorough physical and chemical description of the water cycle, and Mintz and Serafini (1992) recognizing the importance of water storage in the land when they published a global, monthly climatology of world water balance.

b. Remote Sensing of the Global Water Cycle

In 1958 NASA's Explorer 1 satellite launched and provided imagery of clouds and snow cover that revolutionized the way scientists thought about the water cycle. Other satellites soon began to improve our ability to observe Earth from space, and in 1972 the Blue Marble photograph from Apollo 17 inspired a new generation of Earth scientists and conservationists. During that seminal period of space exploration, the study of hydrology at continental to global scales began to accelerate. The difficulty in extrapolating limited point observations to those scales soon became clear, which was one of the motivations for satellite remote sensing of the global water cycle, and, more broadly, the entire Earth system (Famiglietti et al. 2015).

The first several satellites that were useful for studying the water cycle were not designed for that purpose. The TIROS-1 satellite delivered fuzzy, black-and-white images of Earth in 1960, which elucidated the large-scale patterns of cloud and snow cover. The NASA/USGS Landsat series of satellites, which began in 1972, has provided increasingly higher resolution imagery that has been useful for delineating and monitoring the extent of snow cover, glaciers, surface water bodies, different types of vegetation and land cover, and irrigation, and for estimating evapotranspiration. The first satellite in NOAA’s Geostationary Operational Environmental Satellites (GOES) series was launched in 1975, providing visible and infrared imagery that have been essential for weather forecasting and similarly valuable for hydrometeorological studies. As described in section 3, satellite remote sensing now enables global scale observation of precipitation, soil moisture, terrestrial water storage, snow cover depth and snow water equivalent, evapotranspiration, lake elevation, and soon river discharge. The integration of these capabilities has transformed research on the global water cycle. Lettenmaier et al. (2015) provides a detailed overview of the contributions of remote sensing to hydrologic science, while McCabe et al. (2017) describes future prospects in this area.

c. Global Scale Hydrological Modeling

Global modeling of the water cycle is motivated by multiple considerations. For one, we cannot currently observe the water cycle globally with adequate resolution, accuracy, and continuity. While remote sensing can provide global coverage, the observations themselves typically are derived using retrieval algorithms that have to be calibrated and require simplifying assumptions, both of which introduce error. Second, global models can be used to investigate different climate change or paleoclimate scenarios and test sensitivities to natural properties and anthropogenic influences. Third, our proficiency in modeling the water cycle at the global scale provides insight into our understanding of the Earth system. Fourth, global land surface models can be coupled to Earth system models or used to integrate data from multiple observing systems. Finally, running a hydrological model at the global scale complements remote sensing or in-situ observing systems that are limited by both cost and technology in their ability to provide continuous spatial and temporal coverage. Such models, which range from extremely simple water budget equations to physically-based, coupled land-atmosphere-ocean models comprising tens of thousands of lines of code, have their own weaknesses. In particular, they are constructed using our sometimes-flawed understanding of physical processes, they rely on their own simplifying assumptions, and their accuracy is limited by that of the input parameters and meteorological variables. Nevertheless, global hydrological models have supported a huge number of water cycle studies over the years, and they enable sensitivity studies and the analysis of scenarios that could never be tested in the real world.

Global hydrological models were originally developed in order to improve the lower boundary condition for atmospheric models. One of the first was Manabe's (1969) "bucket model", which he incorporated into the Geophysical Fluid Dynamics Laboratory's general circulation model, yielding estimates of the global rates of land surface evaporation. By the mid-1980s, it was understood that simplistic land surface representations were creating systematic errors in simulated evapotranspiration and hence the overlying atmosphere, leading to the development of more sophisticated schemes (Dickinson, 1984). In particular, the Simple Biosphere model (SiB; Sellers et al. 1986) and the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al. 1986) enabled simulation of the transfers of mass, energy, and momentum between the atmosphere and the land surface. Thirty-two years later elements of SiB and BATS, the first soil-vegetation-atmosphere transfer schemes, are obvious in the code of many modern land surface models. Incorporating the influence of topography on runoff generation and other processes was one of the next key milestones (Famiglietti and Wood, 1991) along with ways to represent such spatially and vertically distributed processes statistically (Famiglietti and Wood, 1994). Around the same time, Koster and Suarez (1992) demonstrated a “tiling” approach to modeling multiple different vegetation types within a single grid pixel. An explosion of new land surface models ensued, which brought about the need for model intercomparison projects. The Global Soil Wetness Projects (GSWP) 1 & 2 (Dirmeyer et al. 1999; 2006a) focused on soil moisture and included 10 and 15 models, respectively, each with their own unique set of advances and simplifications. The Water Model Intercomparison Project (WaterMIP; Haddeland et al. 2011) emphasized water cycle fluxes and included five coupled models as well as six offline (land only) models.

Owing to exponential increases in computing power, incremental improvements in our understanding of water and energy cycle processes, and the availability of more accurate and higher resolution forcing and parameter datasets, many global land surface models now run routinely (e.g., Alcamo et al. 2003; Rodell et al. 2004) and most weather forecasting agencies have implemented advanced land surface modules into their operational systems. Software packages like the Land Information System (LIS; Kumar et al. 2006) now allow non-expert users to configure and run multiple land surface models for both scientific and practical applications. A handful of land surface models have benefitted disproportionately from a community development approach and/or implementation by multiple operational agencies that foster their continued improvement. Examples include Noah Multiparameterization (Noah-MP; Niu et al. 2011), the Community Land Model (Oleson et al. 2010), and the Joint UK Land Environment Simulator (JULES; Best et al. 2011). Kumar et al. (2017) concluded that this may be causing a convergence of the output from different models.

d. Community Water Cycle Research Initiatives

In addition to these individual efforts, the Global Water and Energy Cycle Experiment (GEWEX) and other international programs have facilitated community initiatives aimed at improving understanding of the global water cycle and its components. Kinter and Shukla (1990) suggested a framework for utilizing ground and space based observations during the first phase of GEWEX towards the goal of improved understanding of the global water and energy cycles. Sub-projects within GEWEX have included global hydrology as an explicit component, such as the Global Soil Wetness Project (GSWP) phases 1 & 2, LandFlux, the Coordinated Enhanced Observing Period (CEOP), and the GEWEX Hydroclimatology Panel (GHP). The International Geosphere-Biosphere Programme (IGBP; 1987-2015) similarly included projects relevant to global water cycle and water resources research, such as the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) and the Global Water System Project (GWSP). However, the Intergovernmental Panel on Climate Change (IPCC), which is perhaps the best known international community Earth science initiative, has focused largely on ground and near surface air temperature variations and trends, and while water cycle impacts have been considered secondarily. Further, a persistent obstacle for studies that is conceived within GEWEX and other community initiatives is that the initiatives themselves typically have little or no funding to support the research. NASA’s Energy and Water Cycle Study (NEWS) program has sought to overcome that issue and combine integrative community research with funding support, towards the goal of quantifying water cycle consequences of global climate change. Another example of that approach was the European Union's Water and Global Change project (EU-WATCH; 2007-2011), which aimed to bring together scientists from the hydrology and related communities to improve quantification and understanding of global hydrological processes.

e. Recent Advances in Global Water Cycle Science

Many of the major advances in global water cycle science in the 21st century have involved (1) assessing changes in the water cycle and the distribution of water resources, (2) science enabled by satellite remote sensing; and/or (3) science enabled by data integrating numerical models with ever increasing spatial resolution and sophistication of process representation. Regarding the first, Vörösmarty et al. (2000) used climate model predictions together with hydrologic and socioeconomic information to assess the vulnerability of water resources to climate change and population growth, with startling results. Many related studies followed, including Vörösmarty et al.'s (2010) reassessment that also considered threats to biodiversity. Allen et al. (2002) analyzed variability of the hydrological cycle during the 20th century in order to evaluate the range of possible 21st century changes. Milly et al. (2002) reported an increasing risk of great floods due to climate change. Bosilovich et al. (2005) and Held and Soden (2006) analyzed climate model output to identify evidence of "intensification" of the water cycle, which refers to the prediction of more intense and rapid cycling of water fluxes in a warming environment. Milly et al. (2008) warned that water management, which has heretofore relied on the assumption of stationarity – natural systems fluctuating within an unchanging range of variability – is imperiled by both direct human disturbances and climate change. Brown and Robinson (2011) used a combination of ground, airborne, and satellite datasets to estimate that March and April northern hemisphere snow cover extent decreased at a rate of ~0.8 million km^2 per decade during 1970–2010. GRACE has been used in combination with other data sources to quantify groundwater depletion around the world (Rodell et al. 2009; Wada et al. 2012; Döll et al. 2014; Richey et al. 2015; Chen et al. 2016;

Rodell et al. 2018). Nevertheless, Reager et al. (2016) used GRACE data to show that there was a net increase in non-frozen terrestrial water storage during 2002-2014, which reduced the rate of sea level rise by 15%. Rodell et al. (2015) used an objective optimization approach to combine ground and space based observational datasets with data integrating model output, covering the first decade of the millennium, while simultaneously closing the water and energy budgets at multiple scales. The result was a physically, spatially, and temporally consistent set of estimates of the major fluxes and storages of the water cycle at continental, ocean basin, and global scales (Figure 7). This analysis is useful as a baseline for assessing future changes in the water cycle and for global model evaluations. Other projects have produced global water cycle accountings through the assimilation of data into global coupled or offline models (e.g., Rienecker et al. 2011; van Dijk et al. 2014; Gelaro et al. 2017; Zhang et al. 2018).

Modeling improvements and the unprecedented availability of satellite-based observations have benefitted global water cycle science enormously, but questions and uncertainty remain. For example, while many have predicted an increasing occurrence of drought in a warming environment, Sheffield et al. (2012) reported no significant change in drought over 60 years, setting off an intense debate in the hydroclimate community. Similarly, when Jasechko et al. (2013) used an isotope analysis to estimate that transpiration accounts for 80-90% of evapotranspiration globally, the community responded with a slew of alternate interpretations and analyses (e.g., Sutanto et al. 2014; Coenders-Gerrits et al. 2014).

Future breakthroughs in global water cycle science will continue to be fueled by advances in remote sensing and modeling. Expansion of remote sensing data records is already enabling studies of global change that are less dependent on the sparse network of in situ observations. By

2030, many of these records will be long enough to generate climatologies and to identify trends. This is already happening with soil moisture (e.g., Owe et al. 2008; Dorigo et al. 2012) in addition to snow cover. While there are serious concerns about the decline of ground based networks that are crucial for both long term temporal continuity and calibration of remote sensing retrievals (Fekete et al. 2015), an optimistic perspective is that implementation of advanced observational approaches, including measurements using signals of opportunity and remote sensing from cubesats and unmanned aerial vehicles, will fill gaps and provide a more complete view of the water cycle (McCabe et al. 2017).

6 Coupling of Hydrology with the Atmosphere and Ecosystem

By redistributing surface and subsurface moisture in space and time, hydrological processes have an important control over evapotranspiration at the surface and moisture available to plants. Hence, hydrological science plays a critical role in understanding and modeling land-atmosphere interactions and ecohydrology, the topics of this section discussed below.

a. Coupling of Hydrology with the Atmosphere: Land-atmosphere interactions

Land and atmosphere can interact through exchanges of water, energy, momentum, and biogeochemistry that are influenced by many processes across a wide range of temporal and spatial scales. Understanding and modeling surface fluxes of precipitation, evapotranspiration, sensible and latent heat, momentum, and aerosol particles and trace gases, as well as the processes that control these fluxes are all important for advancing the study of land-atmosphere interactions. In the context of this monograph on progress in hydrology, this section focuses mainly on land-atmosphere interactions related to soil hydrological processes such as soil moisture, groundwater, and lateral flow. We note however that the land surface can interact with the atmosphere importantly through surface albedo, surface roughness, and biogeochemical processes that influence the net energy input to land and surface flux exchanges.

Traditionally, hydrological science has focused on understanding the hydrologic response to atmospheric forcing, as mediated by the landscapes at watershed and basin scales, while atmospheric science has focused on understanding atmospheric dynamical and physical processes that are influenced, to some degrees, by the surface fluxes. Hence, in hydrology, the atmosphere was considered an external forcing and provided as an input to hydrologic modeling while in atmospheric modeling, land surface processes were ignored or simplified to provide lower boundary conditions for atmospheric general circulation models (GCMs). For example, Manabe (1969) developed a bucket model to represent surface hydrology in GCMs, which allows time-evolving surface evapotranspiration to be calculated as lower boundary conditions for GCMs.

The need to improve the lower boundary conditions in GCMs became more recognized in the 1980s from studies that investigated the atmospheric response to land surface conditions (Shukla and Mintz 1982; Rowntree and Bolton 1983; Mintz 1984) and impacts of deforestation on climate (Dickinson and Henderson-Sellers 1988). Efforts to develop land surface models with more physically based representations enabled the role of the land surface on climate to be better understood. For example, including a physical representation of soil moisture variability in a fully coupled ocean-atmosphere-land model, Delworth and Manabe (1993) noted that the presence of an interactive soil moisture reservoir increases the variance and adds memory to near surface atmospheric variables such as humidity. Studies of precipitation recycling in the 1990s using gridded observations and analyses further established the role of the land surface in providing important sources of moisture for continental precipitation in certain regions (Brubaker et al. 1993; Trenberth 1999). Advances in modeling such as development of the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986) and the Simple Biosphere Model (SiB) (Sellers et al. 1986) and observations such as the First International Satellite and Surface Climatology Project (ISLSCP) Field Experiment (FIFE) (Sellers and Hall, 1992) and the Boreal Ecosystem Atmosphere Study (BOREAS) (Sellers et al. 1995) provided impetus for studying land-atmosphere interactions. Readers are referred to Garratt (1993), Entekhabi (1995), Eltahir and Bras (1996), and Betts et al. (1996) for reviews of advances in land-atmosphere interaction research through the 1990s.

With increasing availability of in-situ and remotely sensed observations, gridded global and regional analyses and land data assimilation products, more complex modeling tools, and larger and faster computers, studies of land-atmosphere interactions have advanced more rapidly since the 2000s. More specifically, the role of soil moisture on precipitation, or soil moisture-precipitation feedback, has been investigated extensively using observations and modeling. GCM experiments (Koster et al. 2000b) and observations (Yoon and Leung 2015) showed that in some mid-latitude continental areas during summer, the impacts of the oceans on precipitation can be small relative to the impacts of soil moisture, suggesting that soil moisture memory may provide important predictability for summer precipitation from weather to seasonal time scales.

Locally, soil moisture can influence precipitation through its impacts on the lower level moist static energy (MSE) and the partitioning of surface energy flux between sensible and latent heat fluxes (Betts et al. 1996; Schär et al. 1999). Wetter soils increase the evaporative fraction (EF defined as the ratio of latent heat flux to the sum of the latent and sensible heat fluxes) to moisten the atmospheric planetary boundary layer (PBL) and lower the levels of lifting condensation and free convection, which may trigger convection and enhance precipitation (Findell and Eltahir 2003). Conversely, sensible heat flux is enhanced relative to latent heat flux over drier soils to deepen the PBL and dilute the moist static energy within the PBL. As the PBL grows, more rigorous entrainment of drier air from above the PBL further reduces the MSE within the PBL and reduces the likelihood of convective triggering and precipitation. Changes in cloud cover may further enhance the positive soil moisture-precipitation feedback as increased formation of convective clouds over wetter soils may increase the net radiation at the surface if the reduction of outgoing longwave radiation by the high clouds overcompensates for the reduction of solar radiation due to cloud cover, thus increasing the MSE and convection (Schär et al. 1999; Pal and Eltahir 2001).

Importantly, the sign of the soil moisture-precipitation feedback may depend not only on the partitioning of the surface fluxes, which depends on soil moisture (i.e., surface control), but also on the atmospheric conditions that determine the levels of lifting condensation and free convection (i.e., atmospheric control). The more rapid growth of the PBL over drier soils may allow the PBL to reach the level of free convection and trigger convection and precipitation while convection is prohibited over wetter soils because the level of lifting condensation may never reach the top of the shallow PBL, despite enhanced moisture and MSE by the increased latent heat flux over wetter soils (Findell and Eltahir 2003). Soil moisture can also influence atmospheric circulation through changes in the thermal gradients near the surface that induce sea level pressure gradients. Changes in sea level pressure can influence mesoscale circulation such as the Great Plains low level jet (Fast and McCorcle 1990) and large-scale circulation systems such as the monsoon systems (e.g., Douville et al. 2001). As soil moisture affects convection, it can also induce changes in the large-scale circulation through its impacts on convection and latent heating in the atmosphere.

To quantify the strength of land-atmosphere coupling, Koster et al. (2004; 2006) designed the Global Land-Atmosphere Coupling Experiment (GLACE) that provided an ensemble of GCM simulations following the same simulation protocol. In GLACE, each GCM was used to perform 16 simulations in which soil moisture varies in each simulation based on the precipitation produced by the model (i.e., land-atmosphere interactions are active). In another set of 16 simulations, geographically varying time series of subsurface soil moisture was forced to be the same across the simulations (i.e., land-atmosphere interactions are disabled). Comparison of the intra-ensemble variance of precipitation between the two sets of simulations yields an estimation of land-atmosphere coupling strength for each model. Since GCM representations of atmospheric and land surface processes vary, results from an ensemble of 12 GCMs that participated in GLACE provide a more robust estimate of land-atmosphere coupling strengths. Koster et al. (2004) identified the central U.S., the Sahel, and India as hotspot regions of land-atmosphere coupling (Figure 8). However, the use of 12 GCMs in GLACE also reveals large uncertainty in model estimates of land-atmosphere coupling strengths (Koster et al. 2006; Guo et al. 2006).

The GLACE experiments motivated many follow-on studies to estimate the land-atmosphere coupling strength using observations and modeling experiments. For example, using long-term in-situ measurements from the U.S. Department of Energy Atmospheric Radiation Measurement

(ARM) Program in the Southern Great Plains and FLUXNET sites in the U.S. and Europe (Baldocchi et al. 2001), Dirmeyer et al. (2006b) compared the local covariability of key atmospheric and land surface variables similar to Betts (2004) in model simulations and in-situ measurements. They found that most models do not reproduce the observed relationships between surface and atmospheric state variables and fluxes, partly due to systematic biases in near-surface temperature and humidity. Despite the large inter-model spread and biases in individual models, the multimodel mean captures behaviors quite comparably to that observed. The international Global Energy and Water Exchanges project (GEWEX) Global Land–Atmosphere System Study (GLASS) panel has formed the Local Land–Atmosphere Coupling (LoCo) project to focus on understanding and quantifying these processes in nature and evaluating them with standardized coupling metrics (Santanello et al. 2018).

With availability of global surface soil moisture and precipitation data from satellites, Taylor et al. (2012) evaluated the soil moisture-precipitation feedback, focusing particularly on the least well understood aspect of the feedback loop – the response of daytime moist convection to soil moisture anomalies. They analyzed the location of afternoon rain events relative to the underlying antecedent soil moisture using global daily and 3-hourly gridded soil moisture and precipitation data at 0.25^ox0.25^o resolution to determine whether rain is more likely over soils that are wetter or drier than the surrounding areas. Across all six continents studied, they found that afternoon rain falls preferentially over soils that are relatively dry compared to the surrounding area, implying that enhanced afternoon moist convection is driven by increased sensible heat flux over drier soils and/or increased mesoscale variability in soil moisture, and hence a negative soil moisture-precipitation feedback. In contrast, a positive feedback dominates in six global weather and climate models analyzed, which may contribute to the excessive droughts simulated by the models.

The challenge of modeling land-atmosphere interactions was elucidated by Hohenegger et al. (2009), who compared cloud resolving simulations at 2.2 km grid spacing in which deep convection is explicitly resolved with simulations at 25 km grid spacing with a cumulus parameterization. In their 2.2 km simulations with cumulus parameterization turned off, dry initial soil moisture conditions yield more vigorous thermals that more easily break through the stable air barrier. In contrast, a stable layer setting on top of the PBL that develops over wet initial soil inhibits deep convection. Hence the 2.2 km simulations produce a negative soil moisture-precipitation feedback, but in the 25 km simulations with parameterized convection, deep convection is much less sensitive to the stable layer on top of the PBL because of the design of the convective parameterization so simulations initialized with wet soil moisture produce stronger convection and a positive soil moisture-precipitation feedback. These results highlight the sensitivity of land-atmosphere interactions to model resolution and convection parameterizations.

Land-atmosphere interactions in weather and climate models are also sensitive to representations of land surface processes. With advances in land surface modeling incorporating more complete hydrological processes, the role of surface water-groundwater interactions on land-atmosphere interactions has been studied using models that include representations of groundwater table dynamics (e.g., Anyah et al. 2008; Yuan et al. 2008; Jiang et al. 2009; Leung et al. 2011; Martinez et al. 2016). These studies found that groundwater table variations can induce soil moisture anomalies that subsequently influence ET and precipitation through land-atmosphere interactions.

Integrated hydrology model featuring land surface models coupled to detailed three-dimensional groundwater/surface-water models have also been used to investigate the role of groundwater dynamics and land-atmosphere feedbacks (e.g., Maxwell and Miller 2005). Applying such models to the southern Great Plains, Maxwell and Kollet (2008) found very strong correlations between groundwater table depth and land surface response in a critical zone between 2 and 5 m below the surface, which could then influence land-atmosphere interactions. Miguez-Macho and Fan (2012) found that groundwater can buffer the dry season soil moisture stress in the Amazon basin, with important effects on the dry season ET. With the long memory, groundwater table can potentially provide an important source of predictability for precipitation and other water cycle processes.

Besides groundwater dynamics, the impacts of lateral flow on land-atmosphere interactions have also been investigated using detailed hydrology models, as lateral flow is typically ignored in one-dimensional land surface models used in weather and climate models. Subsurface lateral flow can have important effects on ET and the partitioning of ET between transpiration and bare ground evaporation through spatial redistribution of soil moisture and groundwater table. Using a continental-scale integrated hydrology model, Maxwell and Condon (2016) found that including lateral subsurface flow in models increases transpiration partitioning from 47% to 62% over the conterminous U.S. With integrated hydrology coupled to atmosphere model in regional domains, the impacts of groundwater dynamics and lateral flow have been investigated in recent studies. In idealized simulations, terrain effects dominate the PBL development during the morning, but heterogeneity of soil moisture and water table can overcome the effects of terrain on PBL in the afternoon and influence the convective boundary layer strongly in wet-to-dry transition zones (Rihani et al. 2015). In case studies of strong convective precipitation events, modeling using coupled atmosphere-integrated hydrology model shows that groundwater table dynamics can affect atmospheric boundary layer height, convective available potential energy, and precipitation through its coupling with soil moisture and energy fluxes (Rahman et al. 2015). Recognizing the importance of subsurface processes on land-atmosphere interactions, groundwater dynamics are now commonly included in land surface models used in climate models, but lateral subsurface flow is still mostly ignored (Clark et al. 2015) though some efforts have begun to introduce parameterizations of lateral flow in land surface models (e.g., Miguez-Macho et al. 2007; Maquin et al. 2017).

Research over the last few decades has greatly advanced understanding and modeling of land-atmosphere interactions. The impacts of initial soil moisture conditions on weather forecast skill (e.g., Trier et al. 2004; Sutton et al. 2006) and seasonal forecast skill (e.g., Fennessy and Shukla 1999; Douville and Chauvin 2000; Ferranti and Viterbo 2006; Della-Marta et al. 2007; Vautard et al. 2007; Koster et al. 2010; Hirsch et al. 2014) through land-atmosphere interactions have been demonstrated. Land-atmosphere interactions have also been found to have important effects on extreme events such as droughts (Hong and Kalnay 2000; Schubert et al. 2004) and floods (Beljaars et al. 1996) as soil moisture anomalies and precipitation anomalies may be amplified through positive soil moisture-precipitation feedback (Findell et al. 2011; Gentine et al. 2013; Ford et al. 2015; Guillod et al. 2015a;b; Taylor, 2015; Hsu et al. 2017). Land-atmosphere interactions can also contribute to summer heat waves (Fischer et al. 2007) as anomalous warm temperatures reduce soil moisture through enhanced ET, and drier soils may subsequently intensify and prolong the heat waves.

Understanding land-atmosphere interactions is also important for understanding the impacts of land use land cover change (LULCC). Based on global observations of forest cover and land surface temperature, forest losses have been shown to significantly alter ET and amplify the diurnal temperature variation and increase the mean and maximum air temperature (Alkama and Cescatti 2016). Consistent findings are obtained using modeling, showing that conversion of mid-latitude forests to cropland and pastures increases the occurrence of hot-dry summers (Findell et al. 2017). The impacts of afforestation in the mid-latitude on climate has also been studied, with results showing the important control of soil moisture on the response (Swann et al. 2012). In water-limited region in which latent heat flux is not able to compensate for the increase in surface temperature due to increase in solar absorption by the darker forest, afforestation can lead to large warming. The latter can induce changes in remote circulation and precipitation by perturbing the meridional energy transport that shifts the tropical rainbelt. Irrigation can have important effects on precipitation locally through its impacts on soil moisture, ET, and surface cooling (e.g., Kueppers et al. 2007; Bonfils and Lobell 2007), and remotely through its impacts on atmospheric moisture transport (e.g., DeAngelis et al. 2010; Lo and Famiglietti, 2013; Yang et al. 2017).

Land-atmosphere interactions can also play an important role in modulating the impacts of global warming. For example, land-atmosphere interactions can enhance interannual variability of summer climate such as summer temperatures because climate regimes may shift as a result of greenhouse warming. The latter can create new wet-to-dry transitional climate zones with strong land-atmosphere coupling (Seneviratne et al. 2006), and GCMs provided some evidences that land-atmosphere interactions will be enhanced in a warmer climate (Dirmeyer et al. 2012). Climate models projected increase in global aridity in the future. This response has been attributed to the larger warming over land relative to the ocean, which increases the saturation vapor deficit over land as moisture over land is mainly supplied by moisture evaporated from the ocean surface, which increases at a lower rate due to the smaller warming (Sherwood and Fu 2014). However, the GLACE-CMIP5 experiments show that the increase in aridity under global warming can be substantially amplified by land-atmosphere interactions through changes in soil moisture and CO_2 effects on plant water use efficiency (Berg et al. 2016).

In summary, land-atmosphere interactions have important implications to weather and climate forecast skill, understanding and predicting extreme events including floods, droughts, and heat waves, and projecting future changes in surface climates such as surface temperature variability and drought and aridity over land. Although both complexity and resolution have increased over time, models still struggle to reproduce the observed surface fluxes (Dirmeyer et al. 2018), suggesting more efforts needed to improve modeling of the behaviors of the coupled land-atmosphere system. Coordinated modeling experiments such as GLACE, GLACE-2, and GLACE-CMIP5 have provided valuable insights on land-atmosphere interactions and their role in predictability and climate change impacts. Coordinated efforts to design experiments such as CAUSES (Clouds Above the United States and Errors at the Surface; Morcrette et al. 2018) focusing particularly on understanding model biases, combined with more systematic use of process-oriented diagnostics and designing observing approaches targeting the data needs for characterizing land-atmosphere interactions (e.g., Wulfmeyer et al. 2018) could prove useful for advancing understanding and modeling of land-atmosphere interactions. Cloud resolving and large-eddy simulations constrained by observations could provide detailed information for improving understanding of the complex processes involved in land-atmosphere interactions in different climate regimes.

b. Coupling of Hydrology with Ecosystems: Ecohydrology

Ecohydrology is the study of the interactions between ecosystems and the hydrological cycle (e.g. Porporato and Rodríguez-Iturbe 2002). Building upon theory and approaches from both hydrology and ecology, ecohydrology is an extension of the study of the water cycle to include its impacts and feedbacks with other ecosystem processes such as biogeochemistry, plant ecology, and climate (Hannah et al. 2004). Though this discipline arose from hydrologic and ecosystem science that dates back more than a century (Rodríguez-Iturbe 2000, Vose et al. 2011), the explicit focus on understanding the processes that couple and feedback between hydrology and vegetation has allowed ecohydrology to make significant advances. This relatively young discipline (e.g. Zalewski 2000) has in common amongst these advances the theme of integrated, multi-disciplinary research focused on the interactions between the biota and the hydrologic cycle.

Ecohydrology has benefitted science and society through improved understanding of the hydrologic cycle, ecosystem function, and how climate change, management, and disturbances impact resources of human value (e.g. Adams et al. 2012; McDowell et al. 2018). Because of the inherent interdisciplinary nature of ecohydrology, it has resulted in significant knowledge gains in fields ranging from biogeochemistry to plant physiology to climate impacts. Ecohydrological research spans from arid environments where water-ecosystem coupling is strongly evident in part through water scarcity (e.g. Newman et al. 2006), to humid environments where ecohydrological conditions result in ecosystems sustaining high biomass and stature (e.g. Brooks et al. 2010).

Ecohydrology is rooted strongly in observations of both hydrologic and ecosystem parameters that respond to each other. Classical hydrologic measurements such as streamflow, precipitation, and evaporation remain a central component of ecohydrology as they are in hydrology, but are often coupled with measurements of plant water sources, transpiration, and ecosystem biogeochemical fluxes to better understand the interacting systems. A frequent focus is on vegetation-hydrology feedbacks with the goal of understanding where and how plants obtain water, and how such water acquisition subsequently impacts the local water cycle (e.g. Brantley et al. 2017). A global review of depth of plant acquisition of water revealed a wide range of rooting depths, with a surprisingly large fraction derived from groundwater (Evaristo and McDonnell 2017, Fan et al. 2017, Figure 9). In addition to a large groundwater support of plant transpiration (Figure 9), ecohydrology has also revealed an additional surprise, that plants use water that is from a distinct pool from the source of stream water (e.g. McDonnell 2017). The two water worlds hypothesis that has emerged from these observations has yielded significant improvements in our understanding of ecosystem function (Berry et al. 2018) and has major implications for how we understand, model, and manage catchment hydrologic cycles. This observation fundamentally improves our knowledge of the hydrologic cycle and its control, and simultaneously informs us on vegetation function.

One focal area of ecohydrology has been to understand how management of ecosystem properties impacts subsequent ecohydrological processes across all terrestrial ecosystems (Wilcox 2010). Ecohydrological management applies to estuaries and coastal waters (Wolanski et al. 2004) to the management of forests to maximize water-based resources (Ford et al. 2011). There is a long-history of investigation into run-off responses to forest harvest (e.g. Bosch and Hewlett 1982; Beschta et al. 2000; Holmes and Likens 2016), much of which falls into the category of ecohydrology due to the coupled nature of the investigation into the interactions of hydrology and vegetation disturbance. Ecohydrology of agricultural and other managed lands is also a critical issue given our growing demand for food and fuel production, and the tight coupling between hydrology and crop yields (Hatfield et al. 2011). Future land-management can benefit from ecohydrological knowledge and forecasts, to better mitigate the consequences of warming temperatures, drought, and associated disturbances on both ecological and hydrological functions of human value e.g. crop production, water yields, and energy supply (Vose et al. 2011; McDowell et al. 2018).

Our changing climate has provided large impetus to understand how ecohydrological functions may change under future conditions (Vose et al. 2011; Wei et al. 2011). Rising temperature is forcing greater evaporative demand (e.g. Trenberth et al. 2014), resulting in greater water stress for ecosystems (Williams et al. 2014). Integration of hydrologic formulations such as Darcy’s law into ecohydrologic frameworks suggests that vegetation stature must decline under increasing evaporative demand, even with no change in the frequency of precipitation droughts (McDowell and Allen 2015); this theory is supported by experimental, observational, and simulation evidence (Allen et al. 2015; Bennett et al. 2015). However, rising carbon dioxide is also increasing water use efficiency (but not growth e.g. Peñuelas et al. 2011; Van Der Sleen et al. 2014), resulting in a shift in the balance of carbon uptake per water consumed that has significant potential hydrologic impacts on soil water content and streamflow (though climate and land use may have larger impacts; e.g. Piao et al. 2007). Thus, ecohydrologic approaches will be valuable for understanding the net impacts of future global change on the hydrologic cycle and its feedbacks with ecosystem functions.

Vegetation disturbances, and their dependence and feedbacks upon hydrology, have become an important ecohydrology research focus in recent years (e.g. Adams et al. 2010). Watershed-scale measurements and process modeling are revealing both increasing and decreasing streamflow responses to vegetation loss via disturbance (reviewed in McDowell et al. 2018). Multiple possible ecohydrologic impacts and feedbacks appear to be underlying these variable responses of disturbances on hydrology. The removal of transpiring vegetation by wildfire, logging, or insect outbreaks are expected to increase streamflow due to reductions in net transpiration from the ecosystem, however, shifts in interception and albedo can allow net infiltration responses to go in the opposite direction, resulting in complex streamflow responses to disturbances (e.g. Molotch et al. 2009; Adams et al. 2012; Bennett et al. 2018). Other global change factors that are a growing focus of ecohydrological research include the impacts of invasive species and land-use change (Vose et al. 2011).

Models play a large role in our understanding and prediction of ecohydrology. Next-generation models of the coupling of water, vegetation and biogeochemistry are emerging that capitalize on the simulation strengths from each discipline. For example, inclusion of rigorous plant hydraulics knowledge from empirical physiology work has allowed much improved representation of plant transpiration and its dependence on rooting depth (e.g. Mackay et al. 2015), and can now be fully coupled to photosynthesis (Sperry et al. 2017). Such models are now being employed to understand how regional drought kills trees (e.g. Johnson et al. 2018). Likewise, the growing frequency and severity of terrestrial disturbances, such as insect outbreaks and wildfires, have driven significant ecohydrological advancement in recent years. The ecohydrologic consequences of these disturbances are large, including vegetation removal, accelerated sediment transport, and changes in the timing and amount of water yields (Adams et al. 2010; Penn et al. 2016; McDowell et al. 2018; Bennett et al. 2018). Using process models, we can better understand how disturbances impact the water cycle (Bearup et al. 2016).

Representation of hydrology in Earth System Models remains challenged by integration of hydrologic and land-surface processes (Clark et al. 2015) and thus an ecohydrologic approach is required to advance model representation. This is particularly true under a non-stationary climate, in which the feedbacks and interactions between climate, hydrology, and vegetation are complex and difficult to test. An important component to bridging the gap between modeling hydrology and ecosystems is the use of ecohydrological benchmarks (Kollet et al. 2017). For example, the most rigorous tests of Earth System Models will require not only hydrologic benchmarks (e.g. streamflow, soil water content) but also of vegetation function (e.g. transpiration, growth). Utilization of new tools such as the International Land-Atmosphere Modeling Benchmarking (ILAMB; Hoffman et al. 2017) and the Protocol for the Analysis of Land Surface Models (PALS) Land Surface Model Benchmarking Evaluation Project (PLUMBER; Best et al. 2015) should greatly accelerate both the rate and knowledge gained through benchmarking of both water and non-water parameters simulated by models. Ultimately, benchmarking against multiple data-constraints crossing multiple biogeochemical cycles (e.g. water, carbon, nutrients) forces models to get the right answers for the right reasons, and is thus a powerful direction forward for ecohydrological modeling (e.g., Nearing et al, 2016).

The interactions between hydrology and biogeochemistry, specifically the water, carbon, and nutrient cycles, are a central component of ecohydrology. Nutrient availability, for example, is critical to growth of aquatic biota, soil microbes, and vegetation, and is simultaneously highly responsive to the hydrologic cycle (Liu et al. 2008; Wang et al. 2015). The movement of nutrients such as nitrogen across land-water gradients is of growing concern, particularly with land-cover and climate changes (Burt et al. 2010). Such changes can have cascading impacts on trophic systems and water quality (Krause et al. 2011). Disturbances are particularly threatening to impact the nitrogen and other elemental cycles (Sollins and McCorison 1981), and thus a strong need for integrated research for prediction and mitigation is required under a future disturbance-regime (McDowell et al. 2018).

Future ecohydrological research will benefit hydrology not only in addressing the linkages between vegetation, nutrient cycles, and water, but through an explicit focus on understanding ecosystem/watershed scale mechanisms driving our observations. To achieve this, ecohydrology must continue to utilize cutting-edge techniques including remote sensing (described in section 3 of this paper), fine and coarse-resolution models, and advanced monitoring and experimental techniques. The long-history of cause-and-effect experiments (e.g. catchment disturbances) must continue to play a strong role, but can be refined to address future ecohydrological threats such as wildfires, insect outbreaks, and climate warming. With these advances, we can expect ecohydrology to continue to advance our knowledge and mitigation options for water and non-water resources of human value under increasing future pressure.

7 Water Management and Water Security

a. The Origins

As already noted in the first section, the concept of the hydrologic cycle appears to have been known since ancient civilizations. As population increased, so did the demand for a steady and reliable source of water. Water as a resource has thus been artificially 'managed' ever since there was such demand for mankind. However, until the advent of hydrology as a proper scientific discipline, most water management practices around the world were relatively ad hoc and lacked sound hydrologic principles. For example, in ancient India, the amount rain in an area was recorded for each year and used as a proxy for estimating food production and taxation rate for the following year (Srinivasan, 2000). In Sri Lanka, giant-sized reservoirs were built in the 1st century B.C. during the reign of King Wasabha (67 – 111 BC). According to historical records, the king built 11 large reservoirs and two irrigation canals of what is known today as perhaps the world's oldest and surviving rainwater harvesting project (de Silva et al. 1995). Thus, the history of hydrology in water management is long and has always been driven by societal needs for maintaining a steady supply of water.

b. Water Management Today

Today, water management owes its foundation to pioneers who developed hydrology as a science during early 20th century. One particular pioneer who must be mentioned for his seminal role in spurring water management is Robert Horton, who performed scientific investigations to solve real-world problems. Horton (1940) had written about infiltration and runoff production that is commonly used today to express runoff generation process from precipitation in many of today's watershed management models. He had also written on erosion, geomorphology, basin response – all of which have directly contributed to the evolution towards physical hydrology-based engineering design of water management systems.

In the current computer-era, the first use of digital computing in hydrology, although driven primarily by scientific investigations, was in the Stanford Watershed Model (Crawford and Linsley, 1966) and the MIT Catchment Model (Harley, 1971). These computer models offered hydrologists and water managers, an opportunity to look at the complex behavior of a river basin more holistically for decision making. Since these early computer models, there have been numerous others developed for hydrologic prediction in water management decision making for flood management (Abbott et al. 1986), irrigation management (Singh et al. 1999), reservoir operations (Yeh, 1985), water quality management (Abbaspour et al. 2007). For a historical overview of current computer models used for watershed management, Singh and Woolhiser (2002) provide a very comprehensive review.

With the advent of 'Dynamic Hydrology' (Eagleson, 1970) as a discipline, hydrology evolved after the 1980s as a more inter-disciplinary topic with closer links to atmospheric science, groundwater science, plant biology, and climate (see sections 2 and 5). Land-atmosphere interactions were recognized of their importance and land surface hydrologic (computer) models were developed. These models, such as the Variable Infiltration Capacity (VIC) model (Liang et al. 1994), Noah (Chen et al. 1996; Ek et al. 2003), Noah-MP (Niu et al. 2011), and the Common Land Model (CLM; Dai et al, 2003) to name a few, opened doors for water managers to explore the role of climate and weather on water management. Unlike traditional hydrologic models, the atmospheric forcings are integrated with the land's response through energy and water fluxes. Such land surface models, including those that are coupled with water management models (e.g., Haddeland et al. 2006; Hanasaki et al. 2006; Voisin et al. 2013), have thus been used in identifying best practices for land or irrigation management (Pielke et al. 2011; Ozdogan et al. 2010), water development and adaptation policy for climate change (Kundewicz et al. 2008), and reservoir management (Hamlet, 2011), just to name a few.

Most recently, with the advent of remote sensing from ground or space platforms (section 3) that can now provide estimates of key hydrologic variables on a global scale, hydrology has begun to experience much broader and more global application in water management. This is primarily because remote sensing from satellites is the only way to monitor changing fluxes of the water cycle in difficult or ungauged regions of the world. In what follows next, water management is broken down thematically into societal application topics.

Reservoir Management

Dams and artificial reservoirs are built to trap a sufficiently large amount of water from the hydrologic cycle to make up for a shortfall when demand for water exceeds the variable supply from nature. Using advancements in hydrologic science, much is now known about the management of post-dam effects on aquatic ecology (e.g., Ligon et al. 1995; Richter et al. 1996; Zhang et al. 2019), geomorphology (e.g., Graf, 2006), floods (e.g., Wang et al. 2017) and droughts (e.g., Wan et al. 2017), and sediment trapping by reservoirs (Graf et al. 2010). Such understanding has consequently improved water management practices for regulated river basins. Yeh (1985) provides a thorough review of the progress of quantitative water management practices that remain a cornerstone for practitioners today even after three decades.

In designing a dam’s physical dimensions, the inflow design flood (IDF) is a major parameter that is derived from analyzing probability of occurrence of flood and precipitation events using historical hydrologic records (Hossain et al. 2010). Also, most of the large dams, especially the hazardous ones located upstream of population centers, are often designed considering the standard Probable Maximum Flood (PMF) (Yigzaw et al. 2013). PMF, by its definition, is the hydrologic response as flow to the previously introduced concept of Probable Maximum Precipitation (PMP). WMO (2009) suggests several methods for PMP estimation: statistical method, generalized method, transposition method, and moisture maximization method (Rakhecha and Singh, 2009). Ever since the wider availability of numerical atmospheric models and reanalysis data of the atmosphere, the dam design and reservoir management community is increasingly marching towards more atmospheric science-based approaches to predict changing risks associated with PMP and PMF (Chen and Hossain, 2018; Rastogi et al. 2017; Chen et al. 2017; Rouhani and Leconte, 2016; Ohara et al. 2011).

Remote Sensing Applications in Water, Food and Disaster Management

As indicated in section 3, from the early days of satellite precipitation remote sensing driven mostly by weather and climate science (Griffith et al. 1978; Arkin and Meisner, 1987) to the modern era of Global Precipitation Measurement (GPM) mission (Hou et al. 2014), the scientific community has made great strides in reducing uncertainty and improving resolution. Consequently, this has opened up a diverse set of applications over the last decade. The global nature of coherent and more accurate satellite precipitation products have now improved water management in river basins where rainfall is abundant but in situ measurement networks are generally inadequate. Building on the success of past satellite remote sensing missions for precipitation, we can now perform global-scale runoff/flood prediction (Wu et al. 2012; 2014), monitor drought/crop yield (Funk and Verdin, 2010; McNally et al. 2017), provide irrigation advisory services (Hossain et al. 2017), monitor landslide risks (Kirschbaum et al. 2012).Remote sensing applications and decision support system have also been utilized in monitoring water supplies stored in snowpacks, drought impacts on agricultural production and groundwater depletion (Schumann et al. 2016).

Transboundary flood forecasting is another area that has recently benefited from application of hydrologic prediction driven by remote sensing, particularly in developing countries (Hossain and Kaityar, 2006). This is because in transboundary river basins, the lack of knowledge about the real-time hydrological state of the upstream nations makes floods more catastrophic than other places. Bakker (2009) has shown that the number of the international river basin floods (i.e., transboundary flood) is only 10% of the total riverine floods. With this small number of occurrences, transboundary floods are responsible for 32% of total casualties, and the affected individuals could be high as 60%. UN-Water (2008) reported that 40% of the global population lives in the 263 shared or transboundary lake or river basins. For transboundary basins, flood forecasting based on satellite remote sensing and hydrologic models has become one of the most economic and effective ways to mitigate floods (Wu et al. 2014). Given the plethora of satellite nadir altimetry sensors that can now measure river levels (JASON-3, Sentinel 3A, 3B, IceSat-2, AltiKa), it appears that altimetry usage with conventional flood forecasting systems will further improve the management of floods.The impacts of food security are felt most seriously in developing countries where people practice subsistence farming. This is where accurate monitoring of growing season conditions can significantly help mitigate the effects of food security in the developing world. These assessments are now being done using remotely sensed monitoring data for precipitation, crop water requirements, and vegetation indices, using hydrologic models and monitoring systems (Budde et al. 2010). For example, MODIS satellite data is now used in developing vegetation indices that provide consistent spatial and temporal comparisons of vegetation properties used to track drought conditions that may threaten subsistence agriculture (Budde et al. 2010).

c. Emerging Issues

The current trend of expanding human settlements, economic activity, population increase and climate change mean that water will continue to get redistributed and artificially managed to the extent that there will be no pristine river basin left today without the human footprint caused by water diversions, barrages, dams and irrigation projects (Zarfl et al. 2014; Kumar, 2015). The evidence is already there. For example, the United States Geological Survey (USGS) records indicate an increase in irrigation acreage from 35 million acres (1950) to 65 million acres (in 2005) in the US alone (Kenny et al. 2009). The latter is equivalent to a withdrawal of 144 million acre-feet (or 177 km^3) of surface and ground water per year. Similarly, there are about 75,000 artificial reservoirs built in the US alone during the last century with a total storage capacity almost equaling one year's mean runoff (Graf, 1999). Around the world, the number of impoundments in populated regions is more staggering and exploding due to needs for economic development (Zarfl et al, 2014).

Studies now clearly show that the regulation of rivers by dams built by upstream nations and the ensuing lack of connectivity between river reaches or the increased time water remains stagnant (in reservoirs) will be most severe in the mid-21st century (Grill et al. 2015). However, the impact on availability of freshwater, which also drives food and energy production, cannot be monitored and managed by downstream nations of such transboundary river basin using conventional approaches to water management. .

8 Future Directions

As we move forward in the 21st century, the expansion of human settlements, economic activity and increasing population mean that water availability will continue to increase in importance. As already evident in the previous sections, scientists, engineers, planners and decision makers will be dealing more and more with a ‘human-water cycle.’ This ‘human-water cycle’ will represent active interplay between humans and nature, therefore inviting new and exciting dimensions to hydrology in the coming decades (Wheater and Gober, 2015). Within hydrologic science, there is increasing recognition of the co-evolution of natural and anthropogenic landscape features and the hydrological response of catchments, and this concept has been termed ‘catchment coevolution’ (Sivapalan and Blöschl, 2017), with the co-evolution era projected from 2010-2030. Advances in hydrologic modeling will continue, supported by more observational data available to constrain the model, improved understanding of hydrologic processes and incorporation of key processes and new approaches, and comprehensive benchmarking of models (Clark et al. 2015). Coincident with these trends, is the new era of ‘big data’ in which computational and theoretical advances are ushering in new learning opportunities, as discussed in Peters-Lidard et al. (2017). Combining big data with new observational platforms, as described in McCabe et al. (2017), will yield important new insights and societal benefits.

In the 50-year anniversary celebration of WRR, Alberto Montanari et al. state that “Water science will play an increasingly important role for the benefit of humanity during the next decades, as water will be the key to ensuring adequate food and energy resources for future generations” (Montanari et al. 2015). They go on to exhort the community that the “target for hydrology in the 21st century must be ambitious. There are relevant and global water problems to solve and there is a compelling need to ensure sustainable development of the human community.”

We are already witnessing some of this ‘ambition’ to solve grand challenge societal problems through the assimilation of climate, weather, numerical modeling and remote sensing into tangible solutions for society. Some of the most exciting prospects for advancing hydrologic science exist at the interfaces with other scientific disciplines, for example: plant biology and ecology for crop yield and ecosystem modeling; oceanography for estuarine process modeling; biogeochemistry for understanding the interactions between carbon and water cycles; and socio-economics for integrating human and water systems (Vogel et al. 2015). All of these advances will likely converge to improve understanding and modeling of the earth system, leading to improvements in weather and climate predictions that exploit land memory from a spectrum of interconnected processes of surface and subsurface hydrology, vegetation, biogeochemistry, and human activities (e.g., irrigation). In the climate projection arena, Bierkens (2015) posits that physically-based continental earth system models (PBCESMs) will converge to support integrated assessments, including, for example, groundwater (e.g., Fan, 2015). For example, in the water management area, there now exists operational satellite remote sensing-based transboundary flood forecasting systems that provide valuable updates of flood risk around the world (Wu et al. 2014; Alfieri et al. 2013) .

However, the human-water cycle is not the only area that needs to experience growth for the future of hydrology. In a recent review of progress and future directions for hydrologic modeling, Singh (2018) cites other areas that need to be studied, such as: Hydrologic impacts of hydraulic fracturing; Transport of biochemical and microorganisms in the soil; Hydrology of hurricanes and atmospheric rivers; and Socio-hydrology. The review goes on to state that “For management of hydrologic systems, political, economic, legal, social, cultural, and management aspects will need to be integrated….” where “both hydrologic science and engineering applications are equally emphasized.”

At the fundamental process level, studies involving isotopes have revealed a complexity of the movement and distribution of water particles in time and space where many of the dynamic connections and disconnections of water stored in the ground remain unexplained today (McDonnell, 2017). For example, at the hillslope scale, the movement of water is often compartmentalized. Runoff from snowmelt can often be from precipitation snowpack that occurred several years earlier. There is clear evidence that plants often remove water through transpiration from immobile pools underground that are not tightly coupled to the infiltration and groundwater recharge processes being modeled today (Brooks et al. 2010). With such process-based questions on hydrology remaining unexplained today, McDonnell argues that future directions in hydrology should also require thinking of newer frameworks that can track both flow and the age of water.

One likely direction toward which hydrology seems to be already evolving is in the area of ‘nexuses’ of resources or themes – such as food-energy-water (the FEW nexus) or climate-energy-water (the CEW nexus) and even the sociology-hydrology nexus (Socio-hydrology). There is no doubt that the future direction of hydrology will be increasingly more multi and inter-disciplinary and draw in fields that have traditionally never interacted with hydrology. For example, freshwater access and nutrition are the foundation pillars of public health. Lack of safe water and sanitation access and malnutrition are intricately linked to water and food security – and can be critical factors behind child mortality and morbidity anywhere. In order to tackle challenges due to compounding factors of lack of sanitation/safe water and nutrition, health management will need to partner closely with agricultural and water management and naturally require strong collaboration from the hydrologic community.

In addressing the ensuing challenges for managing the water, piecemeal approach to hydrology research or investigation will not suffice anymore. To keep water management practices timely and relevant, hydrologic research will most likely be converted into language that encourages uptake by policy makers, practitioners and the public in the real-world out of sheer necessity in the 21st century (Cosgrove and Loucks, 2015; Wheater and Gober, 2015).

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List of Figures

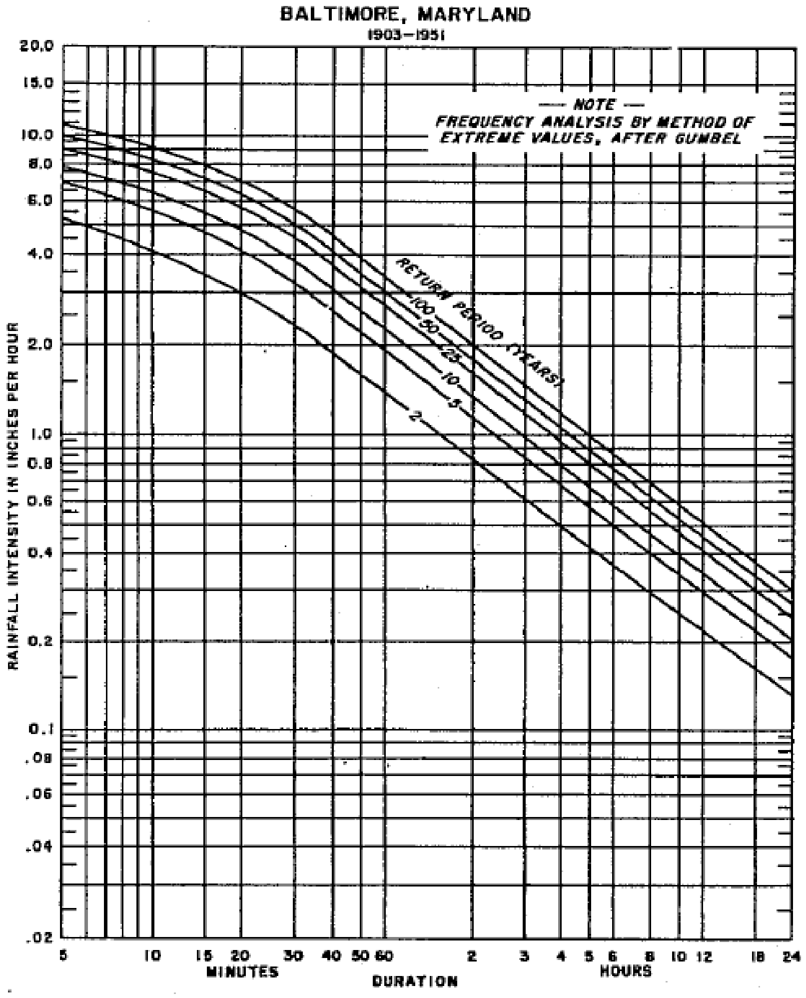

Figure 1. Intensity-Duration-Frequency curve for Baltimore, Maryland from TP-40 (Hershfield, 1961a).

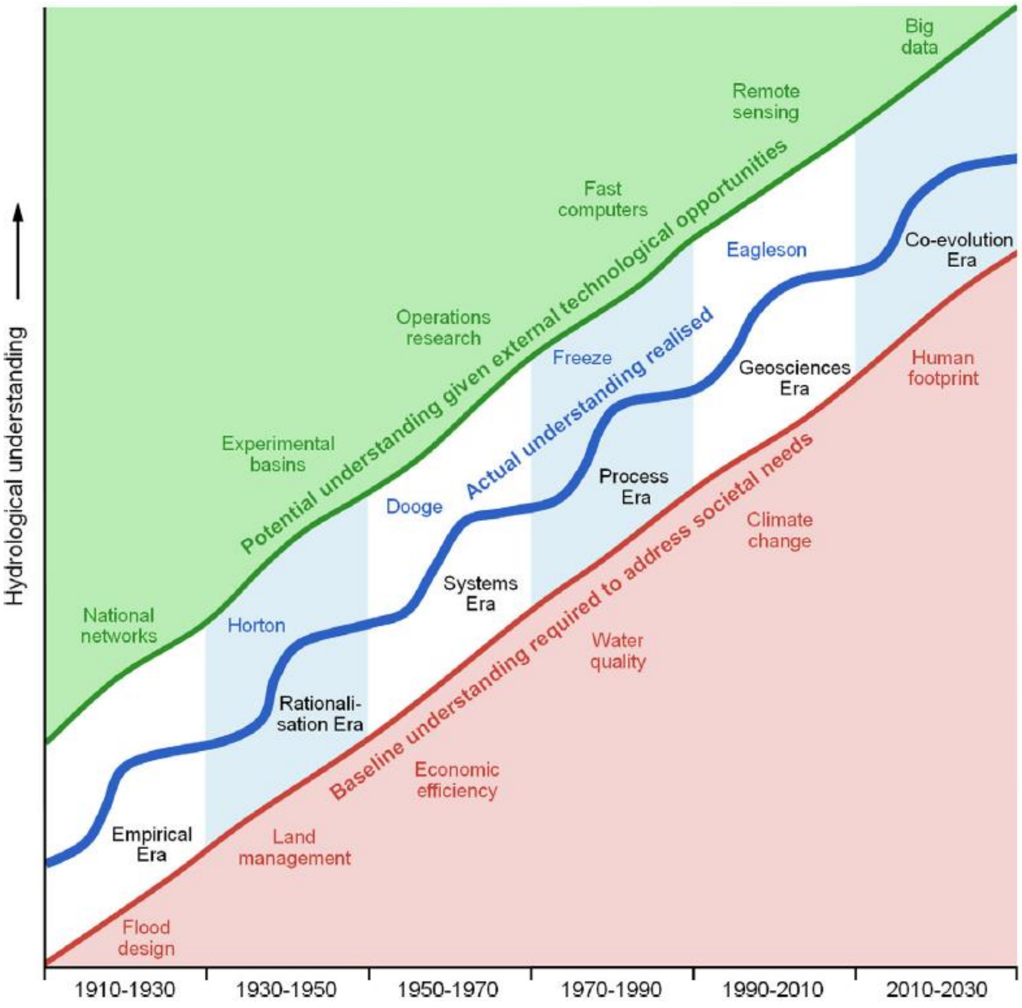

Figure 2. Staircase growth of hydrological understanding sandwiched between baseline understanding required to address societal needs and potential understanding given external technological opportunities. Names in blue epitomize dominant paradigms of the eras. (From Sivapalan and Blöschl, 2017)

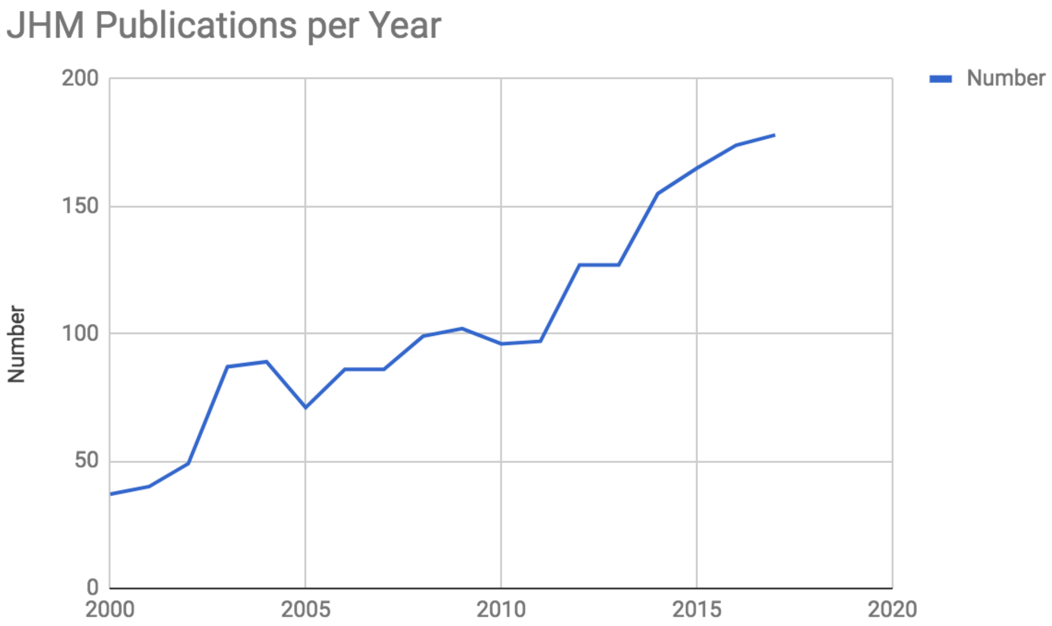

Figure 3. Number of publications per year in the Journal of Hydrometeorology since inception in 2000.

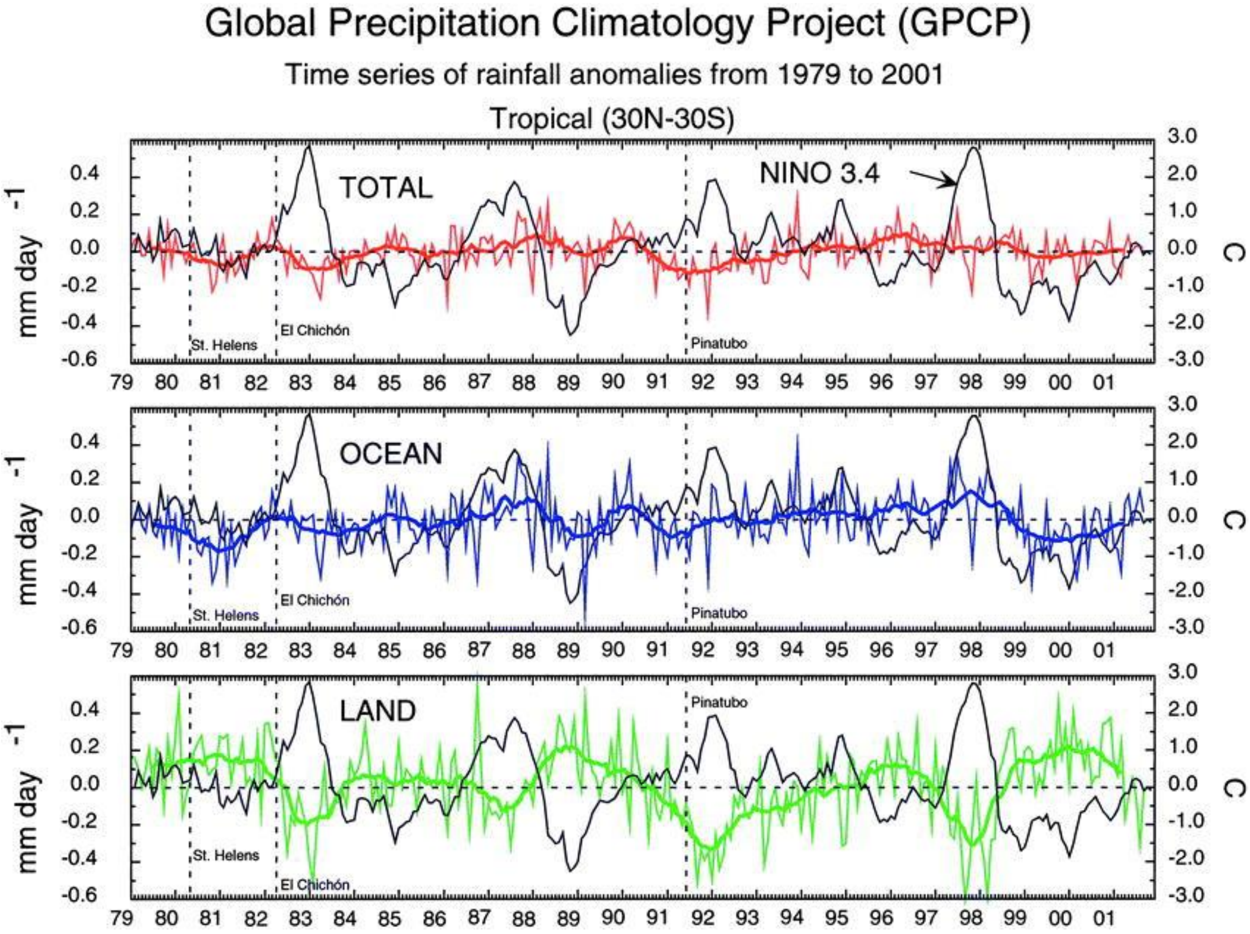

Figure 4. Tropical (30°N–30°S) averages of monthly precipitation anomalies (mm day−1) for (top) total, (middle) ocean, and (bottom) land. Vertical dashed lines indicate the months of significant volcanic eruptions. Black curves in the top, middle, and bottom panels indicate the Niño-3.4 SST index (°C). From Adler et al. 2003.

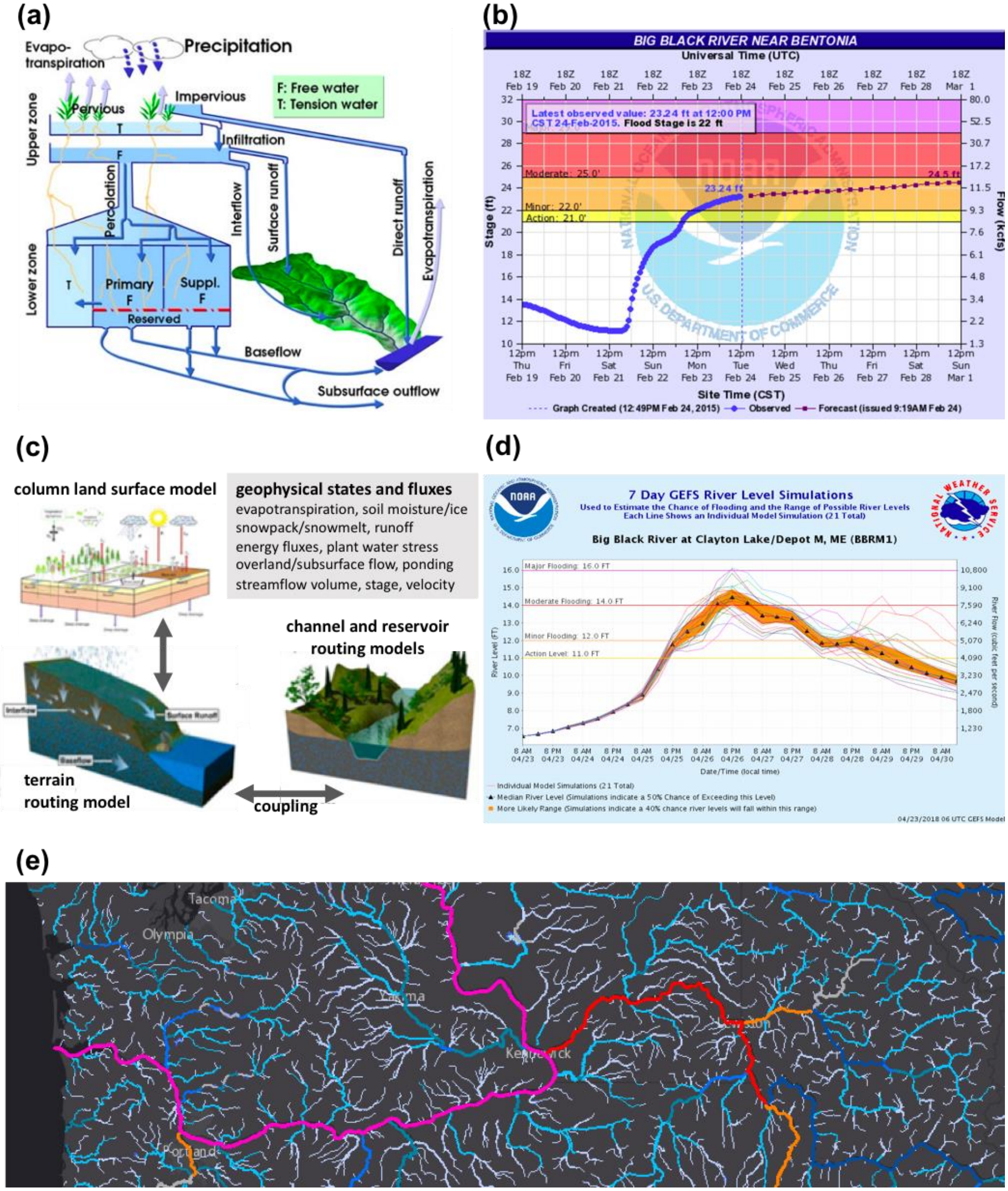

Figure 5. Hydrologic forecasting evolution from (a) conceptual models (e.g., Sac-SMA) and (b) deterministic river flood forecasts to (c) coupled land surface, terrain and channel routing models, (d) ensemble river flood forecasts, and (e) distributed model and stream channel predictions (e.g., the NWS NWM showing the outlet of the US Columbia River basin).

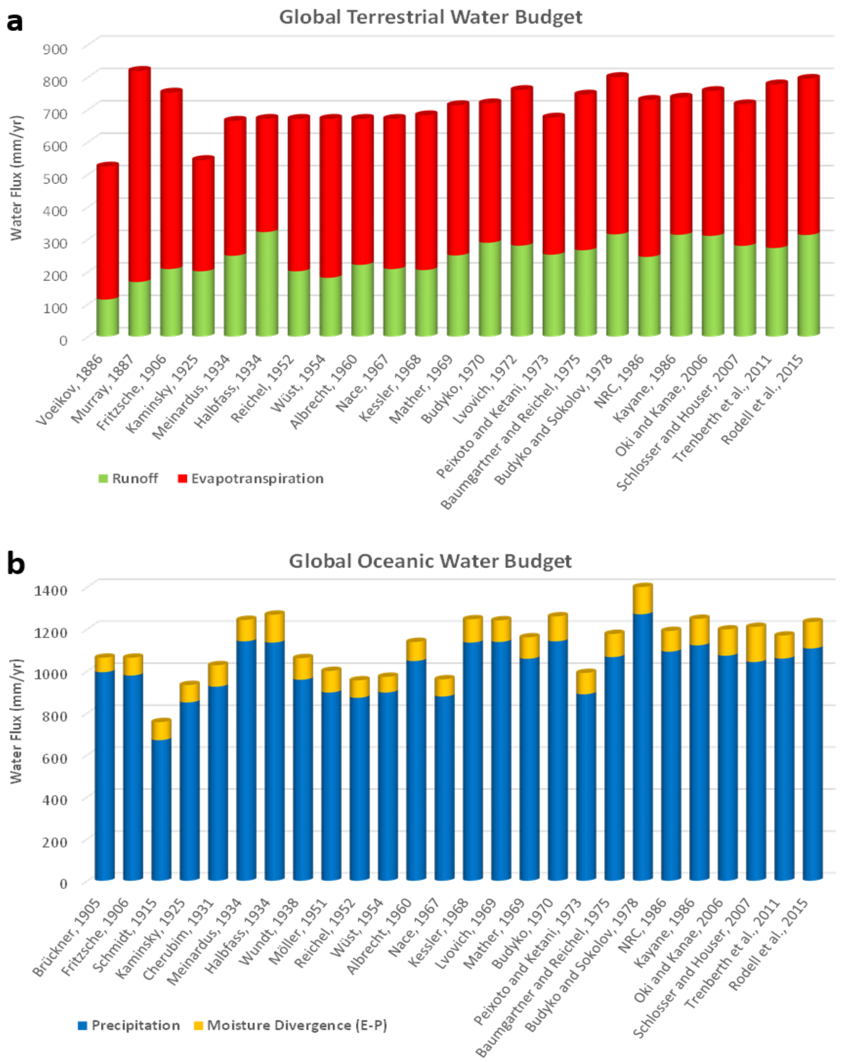

Figure 6. The evolution of global, mean annual water flux estimates (mm/yr) during the past 100+ years, assuming long term changes in atmospheric, terrestrial, and oceanic storages are negligible. Panel a: Global terrestrial runoff (green), evapotranspiration (red), and precipitation (the entire bar). Panel b: Global oceanic precipitation (blue), moisture flux divergence (orange; this is equivalent to evaporation minus precipitation and to terrestrial runoff to the oceans), and evaporation (the entire bar). Note the y-axes of the two panels differ, and that the fluxes in panels a and b are not directly comparable due to the difference in the areas of the global land and global ocean.

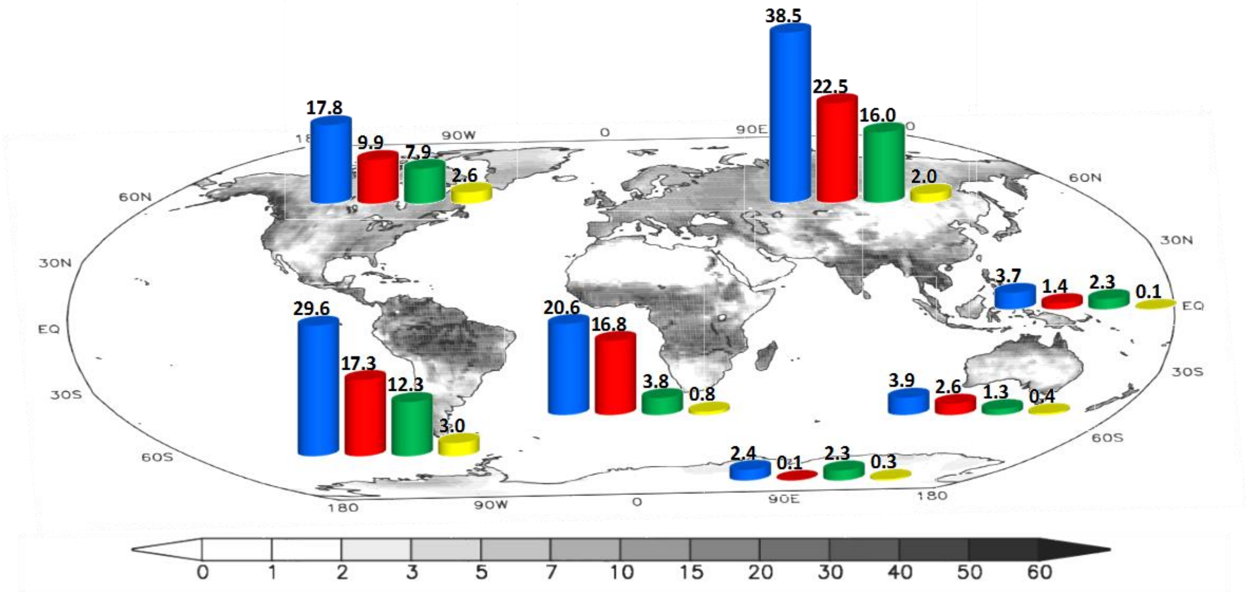

Figure 7. Optimized annual-mean fluxes (1,000 km^3 yr^{-1}) for North America (including Greenland), South America, Africa, Eurasia, the islands of Australasia and Indonesia, mainland Australia, and Antarctica: precipitation (blue), evapotranspiration (red), runoff (green), and annual amplitude of terrestrial water storage (yellow). The background grayscale image shows GRACE-based amplitude (max minus min) of the annual cycle of terrestrial water storage (cm). Copied with permission from Rodell et al. (2015).

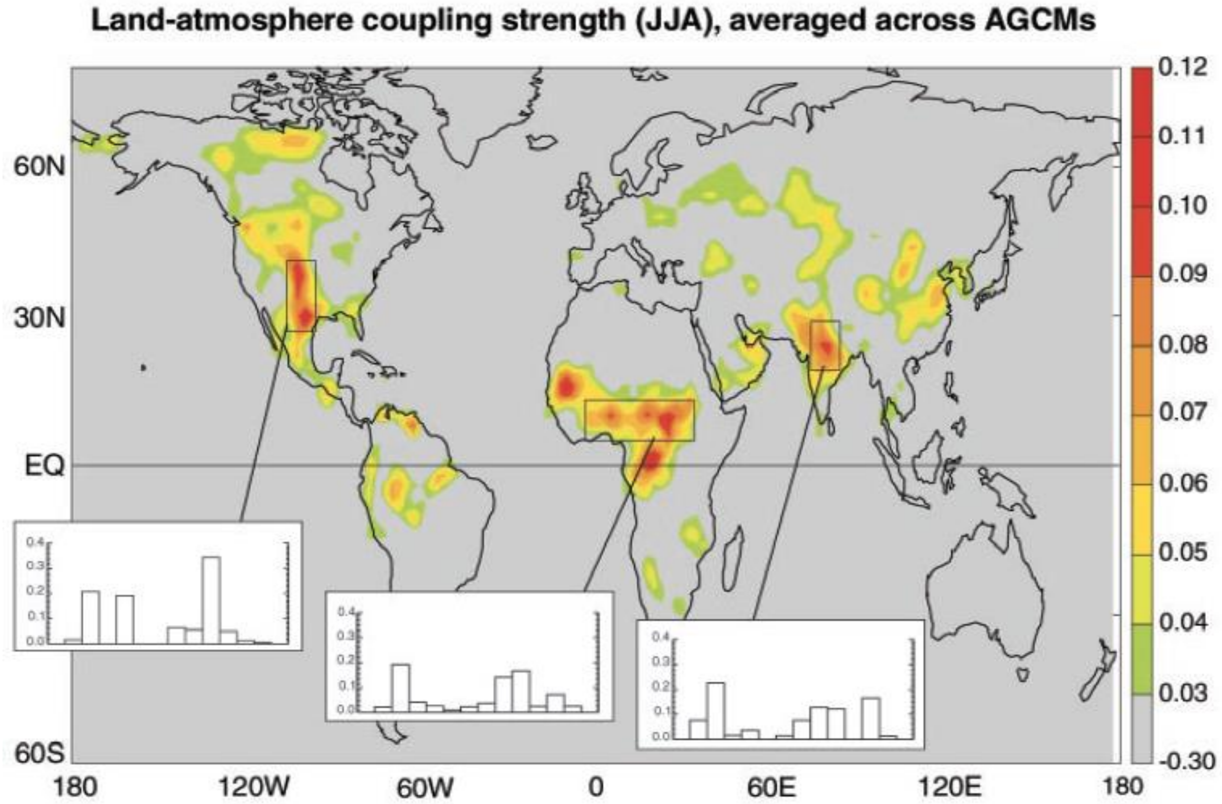

Figure 8. The land-atmosphere coupling strength diagnostic for boreal summer (dimensionless, describing the impact of soil moisture on precipitation), averaged across the 12 models participating in GLACE. (Insets) Areally averaged coupling strengths for the 12 individual models over the outlined, representative hotspot regions. No signal appears in southern South America or at the southern tip of Africa. (Source: Koster et al. 2004).

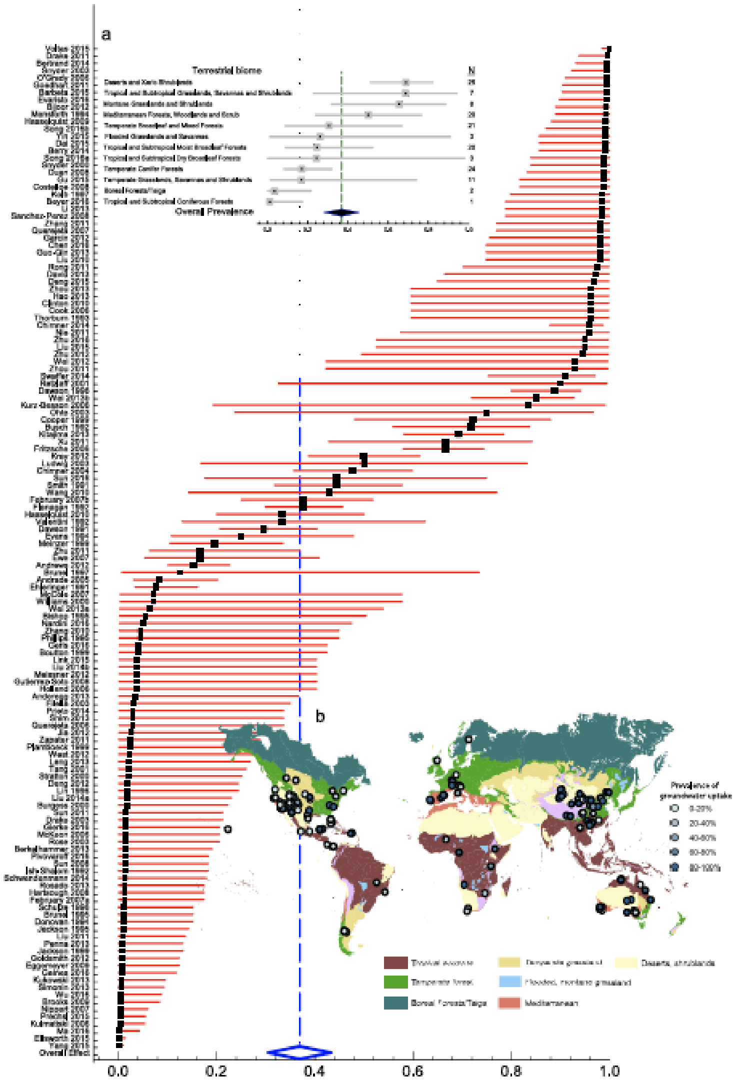

Figure 9. Prevalence of groundwater influence (x-axis: 0 corresponds to no groundwater influence. Main plot, prevalence estimates grouped by source paper (first author-year format). Filled black squares are prevalence point estimates, error bars are 95% confidence intervals (CI, red horizontal lines). Open diamond represents overall prevalence value and its 95% CI is represented by the width of diamond. (a), prevalence estimates grouped by terrestrial biome with N representing corresponding number of sites; (b), Map of prevalence estimates in 162 sites in the global meta-analysis database. (From Evaristo and McDonnell 2017).